EVALUATION OF SYNTACTIC CORE MATERIALS

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Three syntactic core materials were evaluated: 1) HX501 epoxy/A24X glass microballoons, 2) HX501/Carbo-Spheres, and 3) HX592 bis-maleimide/A24X. After optimum B-staging and cure cycles were developed, the following core properties were determined: 1) density, 2) saturation moisture content (140°F/92% RH), 3) compressive strength, and 4) effect of thermal cycling on microstructure and water pickup. Sandwiched core panels were fabricated by cocuring B-staged core sheets between two face sheets of 3-ply graphite/epoxy.

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The following sandwiched core properties were determined: 1) moisture content vs. time (140°F/92% RH), 2) flatwise tensile and short beam shear strengths, and 3) impact resistance. HX501/A24X was found to be superior to the other two materials evaluated as well as Pro-Seal 828, a currently used syntactic core material. All of the sandwiched core panels were damaged by an impact energy of 1-2 ft/lb.

FOREWORD

This Final Report documents work conducted by McDonnell Douglas Corporation (MDC), P.O. Box 516, St. Louis, MO 63166, under Navy Contract N00019-78-C-2050. The work was performed during the period 1 April 1978 through 31 May 1979. The project was administered under the direction of Naval Air Systems Command (NAVAIR), Code AIR-52032D, Washington, DC 20361. The NAVAIR Project Manager was Mr. C. F. Bersch and the Project Monitor was Mr. Max Stander.

The MDC Project Manager was Mr. R. J. Juergens, Branch Chief. The Principal Investigator was Dr. T. C. Grimm.

The laboratory work on this program was directed by Mr. J. F. Harrell.

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SECTION I

INTRODUCTION AND SUMMARY

Syntactic core consists of hollow spheres (usually glass microballoons) in a resin matrix (usually epoxy) sandwiched between two composite laminates. This sandwiched core is being considered for strakes, outriggers, trailing edges, wing fairings, and engine doors. The core material currently used is Pro-Seal 828, an epoxy resin filled with glass microballoons.

As a replacement for aluminum honeycomb, syntactic core offers the following advantages: no adhesive is required, it is impervious to corrosion, it is easily spliced, curved parts can be fabricated without performing, no reinforcement is required for fastener installation, and it is very light weight for thin (<0.080 in.) core. The disadvantages are that it is moisture sensitive, is difficult to produce void-free, and has a low impact resistance. The objectives of the current program were to investigate syntactic core material with: 1) improved moisture resistance, and 2) still lower density.

Three syntactic core materials were selected for evaluation: HX501 epoxy/A24X glass microballoons, HX501/Carbo-Spheres, and HX592 bis-maleimide/A24X.

After optimum B-staging and cure cycles were developed, fully cured sheets were fabricated of HX501 and HX592 neat resins and the three core materials. Sandwiched core panels were also fabricated by cocuring B-staged core sheets between two face sheets of 3-ply graphite epoxy and ultrasonically inspected.

To characterize the fully cured core materials, the following properties were determined:

1) Densities of neat resins and cores;
2) Moisture content vs time (140°F/92% RH to saturation) of neat microballoons, neat resins, and cores;
3) Compressive strengths of cores at room temperature (RT) and 200°F, both as-fabricated and wet (140°F/98% RH for 60 days);
4) Effects of thermal cycling (30 minutes at -67°F followed by 30 minutes at 200°F - one cycle only) on microstructure and water pickup of cores.

Results were compared with Pro-Seal 828. The HX501/Carbo-Spheres had a high density due to many of the spheres being broken during processing. The HX592 bis-maleimide/A24X was very porous, consequently, relatively low strengths were obtained for this material.

To evaluate sandwiched core panels, the following properties were determined.

1) Moisture content vs. time (140°F/92% RH for 72 days), both with and without twice weekly thermal cycling (10 minutes at -67°F followed by 10 minutes at 200°F);
2) Flatwise tensile and short beam shear strengths at RT and 200°F, as-fabricated, wet, and wet after thermal cycling;
3) Impact resistance at RT for energies of 1, 2, 4, and 8 ft-lb.

Results were compared with those for sandwich panels containing Pro-Seal 828 core. All of the sandwiched core panels exhibited low impact resistance. Significant damage resulted from an impact energy as low as 2 ft-lb indicating a need for emphasis in future work.

When processability, density, moisture pickup, dry and wet strengths, and impact resistance were considered, HX501/A24X was found to be superior to Pro-Seal 828 as well as to the other two materials evaluated.

SECTION II

APPROACH

The program plan is shown in Figure 1. Two resins, an epoxy and a bis-maleimide, and two fillers, glass and carbon microballoons, were selected and three syntactic core formulations were prepared. Rolling and optimum B-staging procedures were developed for preparing core sheets. The initial B-staging conditions of each resin were estimated using Differential Scanning Calorimetry (DSC). The optimum conditions were determined by trial and error. Cure cycles were developed for the epoxy and the bis-maleimide resins and fully cured sheets were fabricated of the two neat resins and the three core materials. Sandwiched core panels were also fabricated by cocuring B-staged core sheets between two face sheets of 3-ply graphite/epoxy. These panels were ultrasonically inspected to verify their quality.

The fully cured sheets and sandwiched core panels were cut into specimens. Moisture pickup data (140°F/92% RH) were obtained on the neat microballoons, the fully cured neat resins, the fully cured cores, and the sandwiched cores. The densities of the fully cured neat resins and cores were determined. The core specimens were also used to determine the as-fabricated and wet compressive strengths at RT and 200°F, and the effects of a single thermal cycle between -67° and 200°F on the microstructure and water pickup characteristics. The sandwiched core specimens were also used to determine the flatwise tensile strnegths, short beam shear strengths, and impact resistances. The tensile and shear strengths were determined at both RT and 200°F for each of the following conditions: as-fabricated, wet, and wet after repeated thermal cycling between -67° and 200°F. All impact testing was done at RT on dry panels only.

The test results obtained were compared with those for Pro-Seal 828, and the best syntactic core material was identified.

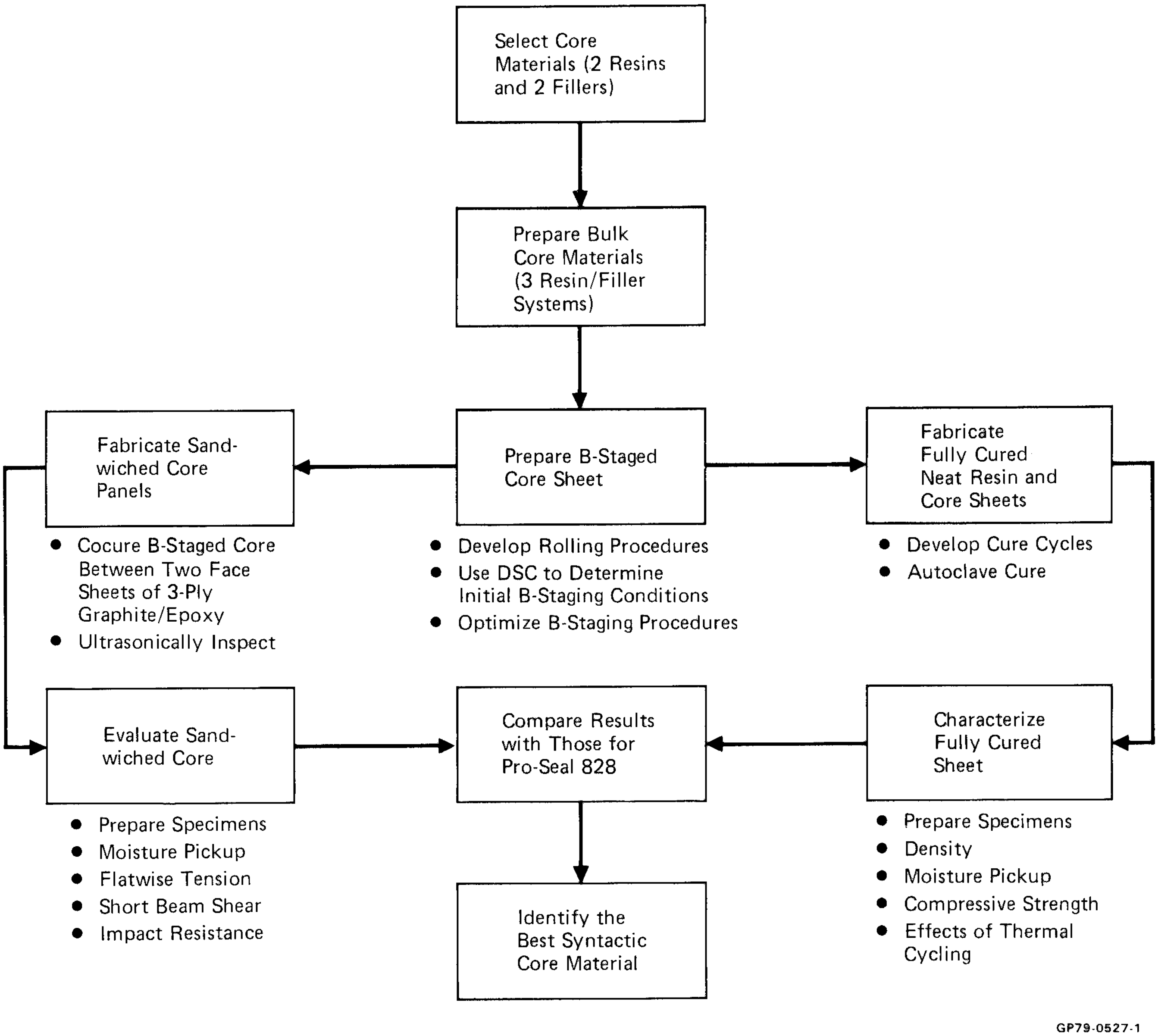

Figure 1. Program Plan

SECTION III

CORE DEVELOPMENT

The three resin/filler systems were formulated by Hexcel using 54% by volume filler. Rolling, B-staging, and curing procedures were developed at MCAIR. Fully cured sheets of each core material were used to determine moisture pickup characteristics (140°F/92% RH), densities, as-fabricated and wet compressive strengths at room temperature (RT) and 200°F, and the effects of thermal cycling on microstructure and water pickup. The results obtained were compared with those for Pro-Seal 828.

1. FORMULATION - The Hexcel Corporation neat resins, HX501 epoxy and HX592 bis-maleimide, were selected chiefly on the basis of their relatively low affinity for water and relatively high compressive strength[1]. These resins are compared to the neat resin used in Pro-Seal 828 in Table 1.

A24X and Carbo-Spheres are both hollow sphere filler systems. The former is a high strength/low density glass microballoon manufactured by 3M Co. The latter is a carbon microballoon manufactured by Versar, a division of General Technologies, Inc. These two microballoon products are characterized in Table 2 along with B40A glass microballoons used in Pro-Seal 828. The microballoons have a nominal diameter of 100 μm (0.004 in.).

The A24X balloons are "floated" before shipment, and not less than 99% by volume are whole. The Carbo-Spheres are estimated to be only 85% whole by volume when received from Versar. The Carbo-Spheres were therefore floated in high-grade acetone at MCAIR to separate out the broken spheres. The floated spheres were shipped to Hexcel in Dublin, CA.

All three syntactic core formulations contained 54% by volume microballoons. Hexcel provided MCAIR with 1 to 2 gallons of each syntactic core material and smaller quantities of neat A24X balloons and neat resins.

The predicted bulk densities of the cured syntactic core materials, including Pro-Seal 828, are given in Table 3. These values were calculated from the following expression:

$$\rho_c = 0.54\ \rho_m + 0.46\ \rho_r \qquad (1)$$

where ρ_c = predicted density of core

ρ_m = average particle density of microballoons

1. Hexcel Corporation, "Syntactic Foam Compression Tests," LSR 93177, 25 July 1977.

TABLE 1. SELECTED RESINS

Neat Resin	Vendor	Chemistry	Nominal Cured Density (lb/ft^3)	Cure Temperature (^oF)
HX501	Hexcel	Epoxy	75	350
HX592	Hexcel	Bis-Maleimide	75	350
Pro-Seal 828	Coast Pro-Seal	Epoxy	75	350

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TABLE 2. SELECTED MICROBALLOONS

Type	Vendor	Material	Coating	Average Particle Density* (lb/ft^3)	Pressure for 10% Collapse** (psi)	Price (\$/lb)
A24X	3M	Glass***	None	14.9	1,000	10.00
Carbo-Spheres	Versar	Carbon	None	8.1	–	40.00
B40A	3M	Glass***	Volan+	23.4	1,000	13.95

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*ASTM D 2840-69 (air comparison pycnometer)
**ASTM D 3102-72 (using glycerol instead of water)
***Water-resistant and chemically stable soda-lime-borosilicate glass
+Methacrylato chromic chloride

TABLE 3. PREDICTED CURED CORE DENSITIES

Syntactic Core (Resin/Filler)	Nominal Cured Resin Density* (lb/ft^3)	Average Particle Density** (lb/ft^3)	Predicted Cured Core Density (lb/ft^3)
HX501/A24X	75	14.9	42.6
HX501/Carbo-Spheres	75	8.1	38.8
HX592/A24X	75	14.9	42.6
Pro-Seal 828	75	23.4	47.4

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*From Table 1
**From Table 2

ρ_r = density of neat resin

assuming 54% by volume microballoons.

2. ROLLING AND B-STAGING - Each syntactic core material was spread between two Teflon-coated fiberglass (CHR-6TB) lined, 1/2 in. metal plates and rolled into 18 x 18 in. sheets, 0.07 in. thick. The HX592/A24X material was very viscous at room temperature and had to be heated to 160°F with the plates before rolling.

The as-rolled sheets could not maintain a shape or thickness and had to be B-staged to make them suitable for subsequent processing. The criteria for optimum B-staging were: 1) stiffness, but conformance to a 3-inch radius without cracking or splitting, and 2) only a small amount of tack.

The initial B-staging conditions were estimated using Differential Scanning Calorimetry (DSC). A mid-point comparison method[2] was used. For this method, gel is assumed to occur at the temperature which is midway between the onset temperature and the exotherm peak temperature (see Figure 2).

The mid-point temperature is related to the heat-up rate by:

$$\log \phi = (A/T_{MP}) + B \tag{2}$$

where ϕ = heat-up rate

T_{MP} = mid-point temperature

A = constant related to activation energy

B = constant related to Arrhenius frequency factor

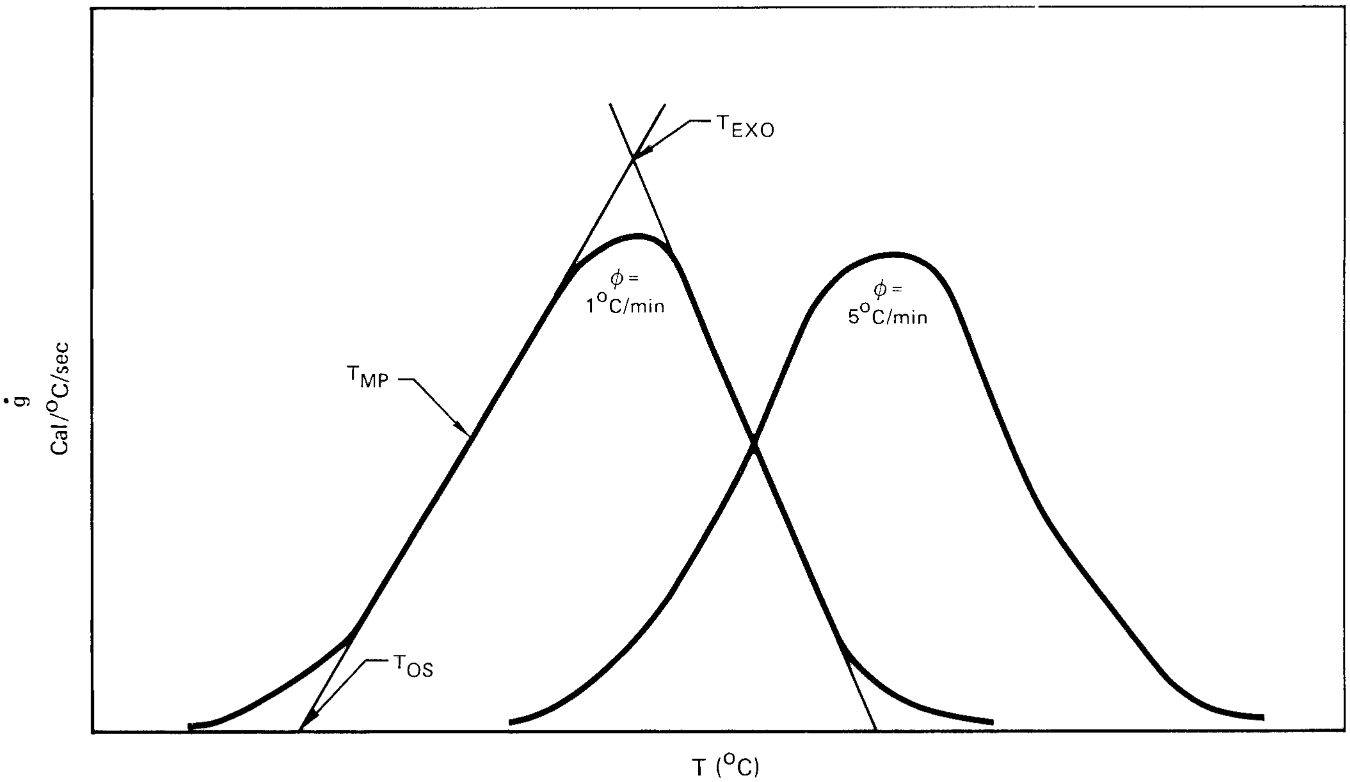
For the resins, values of A and B were determined by running DSC curves on each resin using heat up rates of 2, 5, and 10°C/min, determining mid-point temperatures from the curves, and plotting $\log \phi$ versus 1/T with T in °K. For HX501, A and B were found to be -3637.98 and 9.44571, respectively, and for HX592, they were -8646.56 and 20.74788.

Starting with Eqn. (2) and assuming first-order reaction kinetics, the gel time t in minutes is related to the isothermal hold temperature T in °K by

$$t = cT^2\ 10^{-A/T} \tag{3}$$

where c = constant determined by a summation technique (see Ref. 2). For HX501 and HX592, the values of c were found to be 4.27×10^{-14} and 8.98×10^{-26}, respectively.

2. J. F. Carpenter, "Instrumental Technique for Developing Epoxy Cure Cycles," MCAIR 76-003, Presented at the 21st National SAMPE Symposium and Exhibition at Los Angeles, CA, on 6-8 April 1976.



$\dot{q}$ = Rate of Energy Released (for Exotherm)

T = Temperature

ϕ = Heat-Up Rate

T_{OS} = Onset Temperature

T_{EXO} = Exotherm Peak Temperature

T_{MP} = Mid-Point Temperature, $1/2\ (T_{OS} + T_{EXO})$

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Figure 2. Typical DSC Curves

Eqn. (3) was used to calculate gel time in minutes versus isothermal hold temperature (converted from °K to °F) for each resin. These data are plotted in Figure 3 along with similar data for Pro-Seal 828.

Based on previous in-house work, it was known that Pro-Seal 828 gels after 70 minutes at 150°F. After examining Figure 3, it was assumed that HX501 and HX592 would gel after 70 minutes at 185° and 257°F, respectively. It was also known that Pro-Seal 828 could be successfully B-staged by holding it at 150°F for 30 minutes rather than the full 70 minutes. Consequently, the initial B-staging condition selected for HX501/A24X and HX501/Carbo-Spheres was 30 minutes at 185°F, and the condition selected for HX592/A24X was 30 minutes at 257°F.

The first attempts at B-staging the syntactic core materials resulted in an insufficient cure. Consequently, the hold time was increased beyond 30 minutes until an optimum degree of cure was obtained. The optimum proved to be 75 minutes for all three materials. The optimum B-staging cycles, which were determined by trial and error, are given in Tables 4 and 5.

Good quality HX501/A24X sheet was obtained by rolling and B-staging in accordance with Table 4. This material was relatively nonporous, but somewhat more tacky than desired.

The HX501/Carbo-Spheres sheet, obtained by rolling and B-staging in accordance with Table 4, was relatively porous. Therefore, the bulk material was placed in cartridges and extruded under 90-100 psig pressure prior to rolling in an attempt to reduce the amount of trapped air. As this procedure did not eliminate porosity, another sheet was rolled, heated in a vacuum (<0.1 in. Hg) oven at 150°F for 30 minutes, rerolled, and B-staged. The heating in a vacuum oven greatly reduced the porosity of the material.

The HX592/A24X sheet, rolled and B-staged in accordance with Table 5, was very porous. Neither extruding the bulk material from a cartridge nor heating it in a vacuum oven and rerolling it significantly reduced its porosity. The B-staged material was quite stiff, but flexible enough for sandwich panel fabrication.

3. <u>CHARACTERIZATION</u> - Two fully cured sheets of the three syntactic core materials, one 0.07 and one 0.14 in. thick, were prepared for characterization. The process was as follows:

a) Rolling to a thickness of 0.07 in. (Note: HX592/A24X was rolled hot);
b) Heating in a vacuum oven and rerolling (Note: Not done to HX501/A24X);
c) Autoclave B-staging in accordance with Table 4 or 5;
d) Autoclave curing at 85 to 100 psig and 350 ± 10°F for 120 ± 10 minutes in accordance with Table 6;

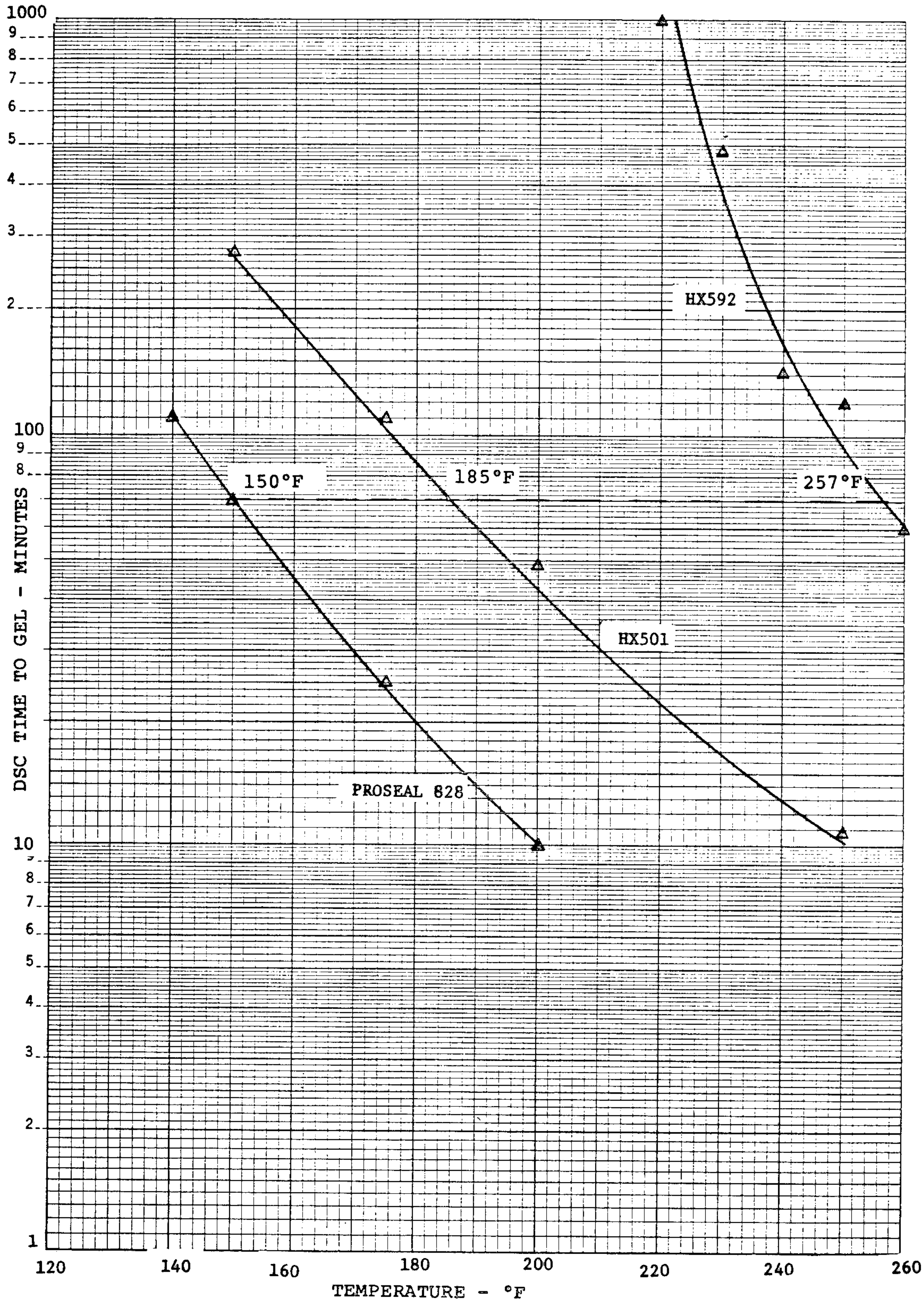

Figure 3. DSC Gel Time Comparisons

TABLE 4. OPTIMUM B-STAGING CYCLE FOR HX501/A24X AND HX501/CARBO-SPHERES

1) Evacuate Bag ($<$0.1 in. Hg).
2) Increase Temperature to 185^{o}F in 50 to 80 Minutes.
3) Hold at 185^{o}F for 75 Minutes. (After 30 Minutes, Increase Autoclave Pressure to 15 psig and Vent Bag).
4) Cool the Assembly as Quickly as Possible, Maintaining a 15 psig Autoclave Pressure.
5) Seal Core Material in a Plastic Bag and Put in Freezer Within 8 Hours After Completion of Step 3.

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TABLE 5. OPTIMUM B-STAGING CYCLE FOR HX592/A24X

1) Set Rolled Sheet on Aluminum Bottom Plate Between Aluminum Dams and Place in an Oven, Preheated to 200°F, for 15 Minutes.
2) Remove from Oven, Allow to Cool, Place Nylon Peel Ply on Exposed Surface of Sheet, and Turn Sheet Over.
3) Place Back in Oven, Preheated to 200°F, for 90 Minutes. (At Same Time, Preheat Aluminum Top Plate to 200°F).
4) Remove from Oven, Add Nylon Peel Ply and Heated Aluminum Top Plate, Tape Assembly Together, Allow to Cool, and Place in Vacuum Bag.
5) Evacuate Bag ($<$0.1 in. Hg).
6) Increase Autoclave Pressure to 15 psig and Vent Bag.
7) Increase Temperature to 257°F at a Rate of 2°F/Minute.
8) Hold at 257°F for 75 Minutes.
9) Cool the Assembly as Quickly as Possible, Maintaining 15 psig Autoclave Pressure.
10) Seal Core Material in a Plastic Bag and Put in a Freezer Within 8 Hours After Completion of Step 8.

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TABLE 6. CURE CYCLES FOR SYNTACTIC CORE MATERIALS AND SANDWICH PANELS

1) Evacuate Bag (<0.1 in. Hg).
2) Increase Autoclave Pressure to 10 to 15 psig.
3) Increase Temperature to 250 ± 10°F in 30 to 85 Minutes.
4) When Temperature Reaches 230°F, Increase Pressure to 85 psig. (Vent Bag When Pressure Reaches 25 psig or Greater).
5) Hold at 240 ± 10°F and 85 psig (Vented Bag) for 60 to 70 Minutes.
6) Increase Temperature to 350 ± 10°F in 20 to 55 Minutes.
7) Hold at 350 ± 10°F and 85 psig (Vented Bag) for 2 Hours.

Postcure for HX592/A24X

1) Evacuate Bag (<0.1 in. Hg).
2) Dump Autoclave Pressure.
3) Hold at 350 ± 10°F for an Additional 8 1/2 Hours.

Postcure for HX501/A24X and HX501/Carbo-Spheres

1) When Initial Cure Cycle is Completed, Cool the Assembly at a Rate Such That 200°F is Reached in Not Less Than 30 Minutes Maintaining a Minimum Autoclave Pressure of 10 psig.
2) Remove Assembly From Autoclave and Place in an Air-Circulating Oven, Preheated to 350 ± 10°F, for 8 ± 1/2 Hours.

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e) Post-curing at $350 \pm 10°F$ for $8 \pm 1/2$ hours in accordance with Table 6.

The autoclave layup for HX501/A24X and HX501/Carbo-Spheres is shown in Figure 4. The layup for HX592/A24X was identical, except that the 1/2 in. gap was eliminated in an attempt to reduce the porosity in the HX592/A24X material, making these sheets 14 x 13 in. rather than 13 x 12 in. The 0.14 in. sheets were prepared by stacking and cocuring two B-staged, 0.07 in. sheets.

The cured sheets were cut into test specimens with a diamond cutoff wheel. These specimens were then used to determine moisture pickup data, densities, as-fabricated and wet compressive strengths at RT and 200°F, and the effects of a single thermal cycle on microstructure and water pickup.

A fully cured sheet of each neat resin, HX501 and HX592, was also prepared. These 0.07 in. thick sheets were made by vacuum melting the resin in a mold and curing (without B-staging) and postcuring like the corresponding syntactic core material. These sheets were cut into test specimens, which were used to determine moisture pickup data and densities. Moisture pickup data were also obtained on neat A24X balloons and Carbo-Spheres.

a. Density - The densities of the two neat resins and the core materials were determined on six 2 x 2 x 0.07 in. specimens of each material. The specimens were weighed to the nearest milligram after a 24 hour drying period at $275 \pm 10°F$. The average measured values are given in Table 7, along with values for the Pro-Seal 828 neat resin and core. The predicted values for the core materials are also listed.

Table 7 shows that, with the exception of HX501/Carbo-Spheres, the measured core densities were within 10% of those predicted. The reason for the large difference (56.0%) for Carbo-Spheres containing core was that many of the spheres were broken during processing.

b. Moisture Pickup - The same specimens used to measure density were used to determine moisture pickup. Immediately after obtaining dry weights, the test specimens were placed in a Blue-M humidity cabinet maintained at 140°F and $92 \pm 4\%$ RH. Four specimens of each material were periodically removed in pairs from the humidity cabinet, wiped dry, and weighed to the nearest milligram. The pairs used for measurement were alternated. When measurements indicated that specimens were saturated, all six specimens were removed, wiped, and weighed. Two of these specimens had not been disturbed during the periodic moisture measurements. Average moisture content, in percent by weight, was determined versus time from the wet and dry measurements.

Moisture pickup data were also obtained on neat A24X, Carbo-Spheres, and B40A microballoons. The microballoon samples were contained in 50 ml beakers.

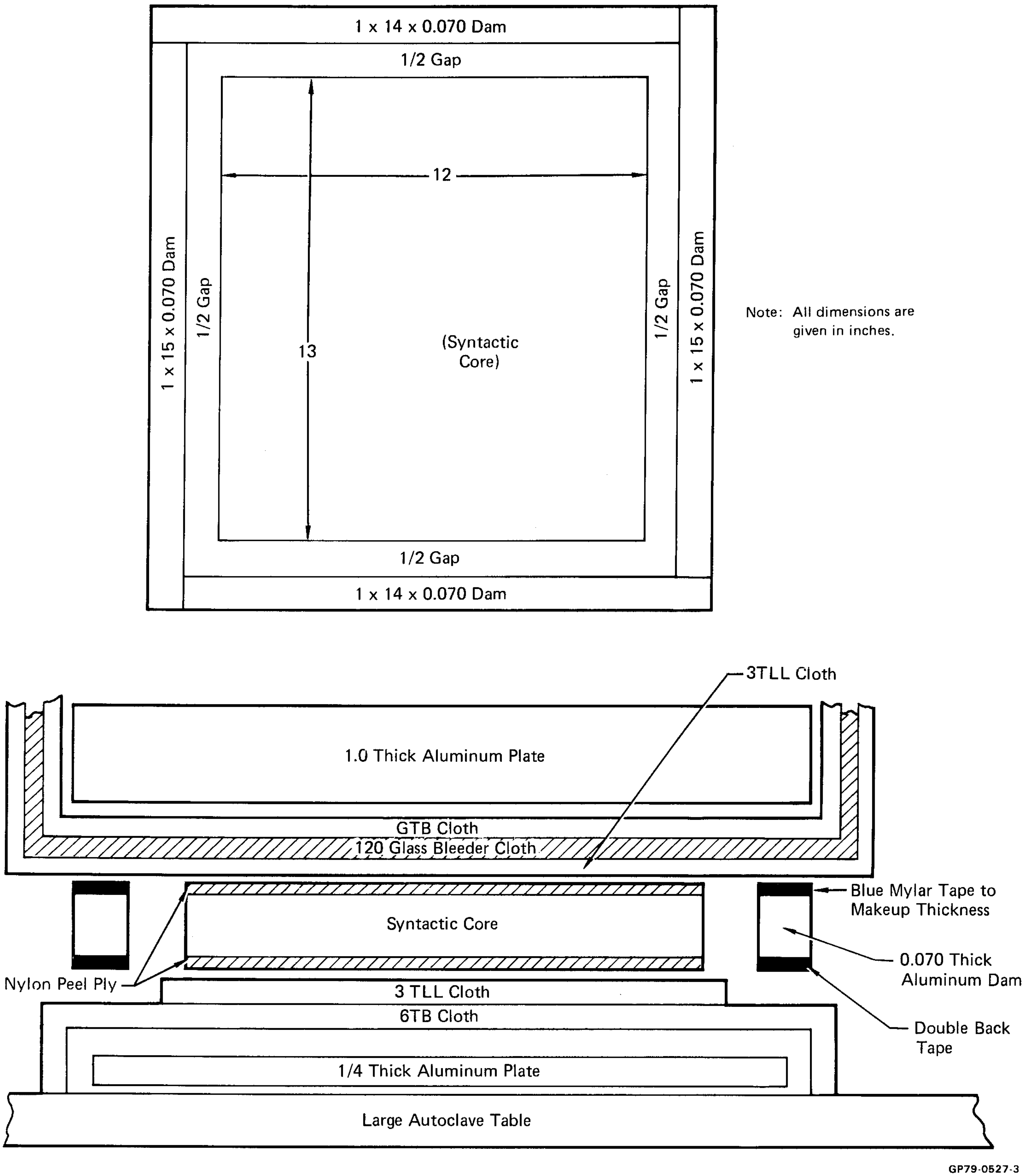

Figure 4. Autoclave Layup for Syntactic Core Sheet

TABLE 7. DENSITIES OF FULLY CURED NEAT RESINS AND CORES

Material	Measured Density		Predicted Density* (lb/ft^3)	Difference** (%)
	(lb/in.^{3})	(lb/ft^3)		
HX501 Neat Resin	0.0481	83.1	–	–
HX592 Neat Resin	0.0454	78.5	–	–
Pro-Seal 828 Neat Resin	0.0456	78.8	–	–
HX501/A24X	0.0271	46.8	42.6	+9.9
HX501/Carbo-Spheres	0.0350	60.5	38.8	+56.0
HX592/A24X***	0.0247	42.7	42.6	+0.2
Pro-Seal 828	0.0278	48.0	47.4	+1.3

*From Table 3

**(Measured-Predicted)/Predicted

***Porous

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The periodic moisture pickup data for neat microballoons, fully cured neat resins, and fully cured core materials are plotted in Figures 5, 6, and 7. The saturation water contents are tabulated in Table 8.

Table 8 shows that:

1) Carbo-Spheres have a high saturation moisture content.

2) Glass spheres have a low saturation moisture content.

3) The HX501 and HX592 neat resins have saturation moisture contents about 50% less than Pro-Seal 828 neat resin.

4) As expected from the microballoon and neat resin data, the HX501/Carbo-Spheres core has a high saturation moisture content, but the HX501/A24X and HX592/A24X cores have saturation contents about 50% less than Pro-Seal 828.

Table 8 also reveals that the predicted water content was somewhat larger than the measured content for HX501/A24X and Pro-Seal 828, and smaller for the other two core materials. These differences, however, are small enough to be attributed to experimental error.

c. Effects of Thermal Cycling - The syntactic core specimens, which had been used in the moisture pickup tests, were subjected to a single thermal cycle, between -67° and 200°F, to determine the effects this might have on the moisture pickup and the microstructure. The specimens were placed in a cold chamber maintained at -67°F, removed after 30 minutes and placed in an oven maintained at 200°F, removed after 30 minutes and allowed to air cool, and returned to the humidity cabinet maintained at 140°F/92% RH. Pairs of specimens were periodically removed from the humidity cabinet, wiped dry, and weighed, until specimen weights stabilized, indicating that specimens were saturated. One specimen of each core material was then cross sectioned and photographed at a magnification of 100X.

The differences in saturation water contents, before and after thermal cycling, are given in Table 9 and the photomicrographs are shown in Figure 8. Although the thermal cycle apparently caused a 0.4 ± 0.1% by wt. increase in saturation contents of all four core materials (see Table 9), the photomicrographs (see Figure 8) did not reveal any cracking of the microstructures.

An examination of Figure 8 does reveal a large number of broken Carbo-Spheres and porosity in the HX501/Carbo-Spheres and HX592/A24X cores. Neither of these imperfections were caused by the humidity exposure and/or the thermal cycle.

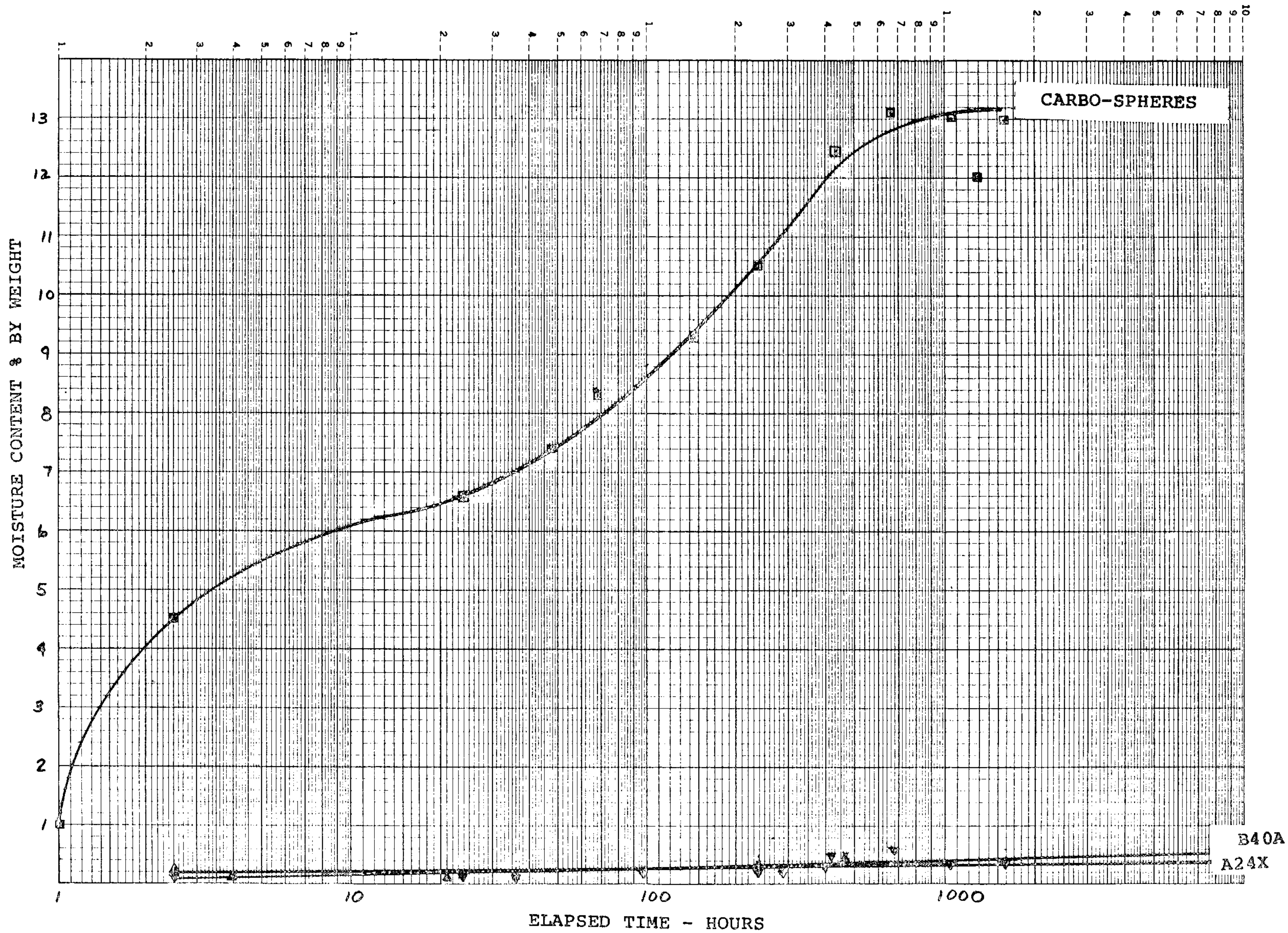

Figure 5. Moisture Pickup Versus Time at 140°F/92% RH for Neat Microballoons

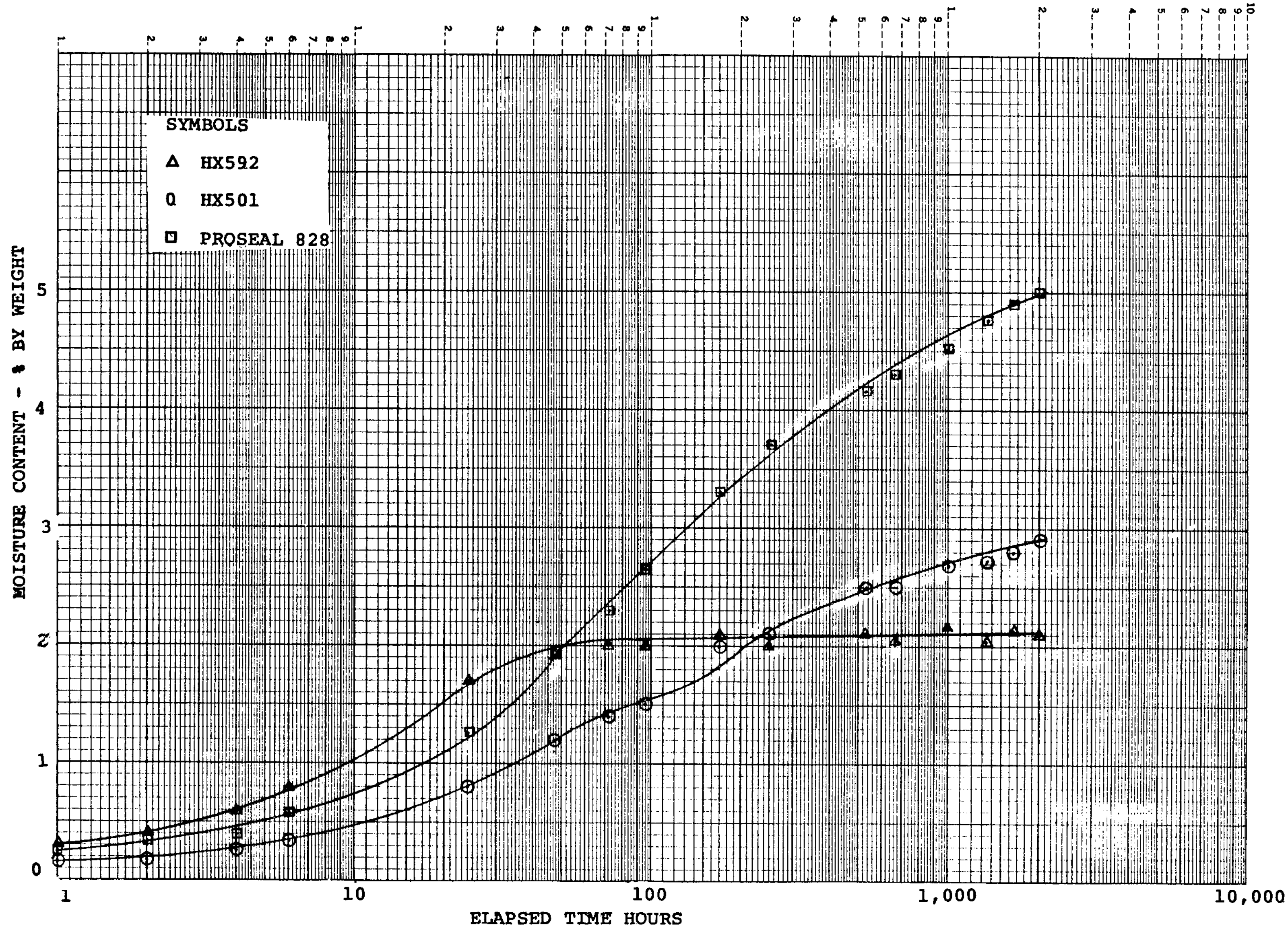

Figure 6. Moisture Pickup Versus Time at 140°F/92% RH for Fully-Cured Neat Resins

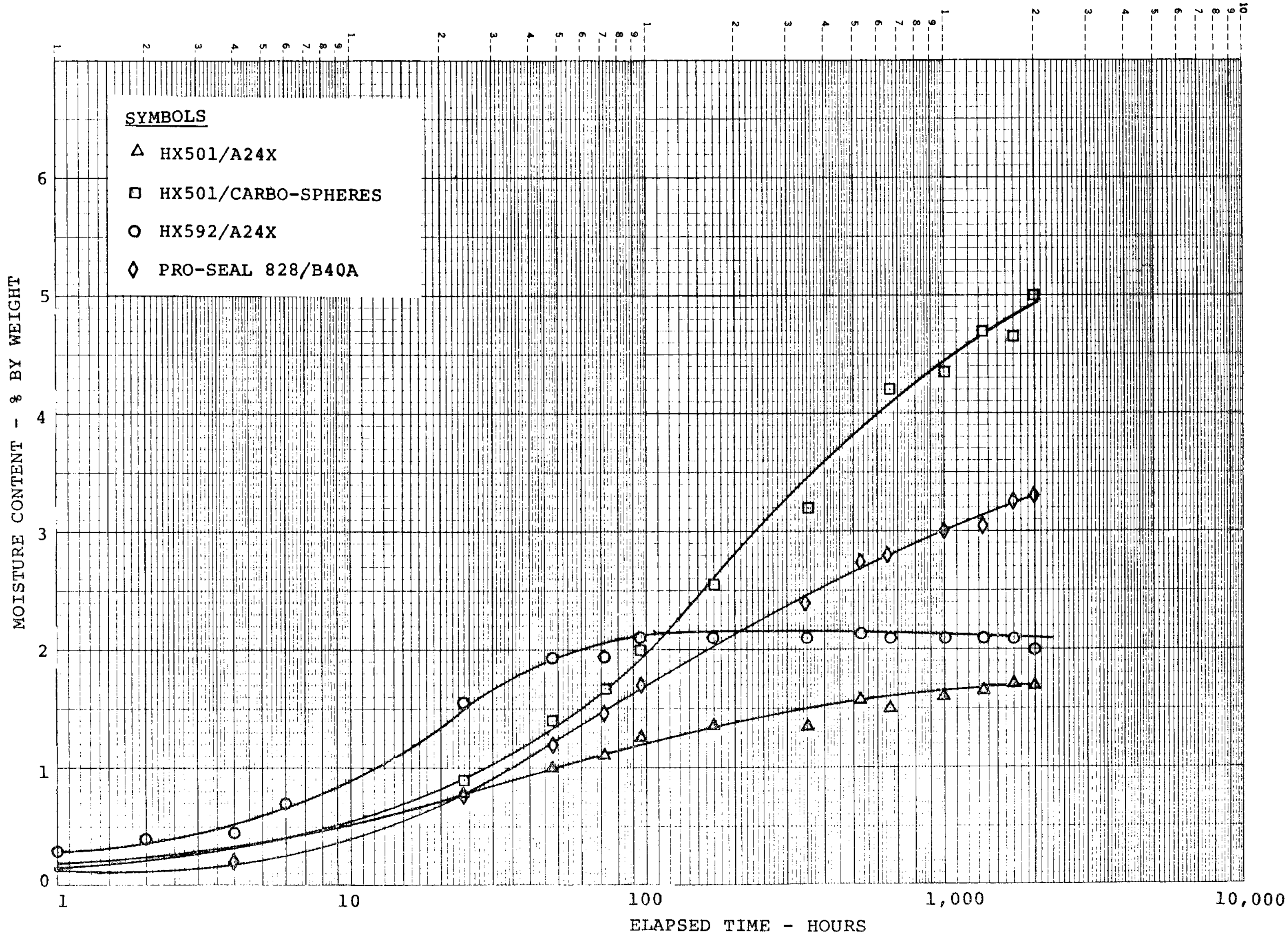

Figure 7. Moisture Pickup Versus Time at 140°F/92% RH for Fully-Cured Syntactic Cores

TABLE 8. MOISTURE CONTENTS OF MICROBALLOONS AND FULLY CURED NEAT RESINS AND CORES - SATURATED AT 140°F/92% RH

Material	Measured Moisture Content (% by Wt)	Predicted Moisture Content* (% by Wt)	Difference** (% by Wt)
A24X Glass Spheres	0.4	–	–
Carbo-Spheres	13.0	–	–
B40A Glass Spheres	0.5	–	–
HX501 Neat Resin	2.9	–	–
HX592 Neat Resin	2.1	–	–
Pro-Seal 828 Neat Resin	5.0	–	–
HX501/A24X	1.7	2.4	–0.7
HX501/Carbo-Spheres	5.0	4.2	+0.8
HX592/A24X	2.1	1.8	+0.3
Pro-Seal 828	3.3	3.8	–0.5

*Based on microballoon and neat resin data and calculated weight fractions. GP79-0597-8

**(Measured - Predicted)

TABLE 9. CHANGE IN CORE SATURATION MOISTURE CONTENTS RESULTING FROM ONE THERMAL CYCLE

Material	Change in Moisture Content* (% by Wt)
HX501/A24	+0.3
HX501/Carbo-Spheres	+0.4
HX592/A24X	+0.5
Pro-Seal 828	+0.4

*(After-Before)

Notes:

1) Thermal cycle consisted of 30 minutes at $-67^{\circ}F$ followed by 30 minutes at $200^{\circ}F$.
2) Specimens were saturated at $140^{\circ}F$/92% RH.

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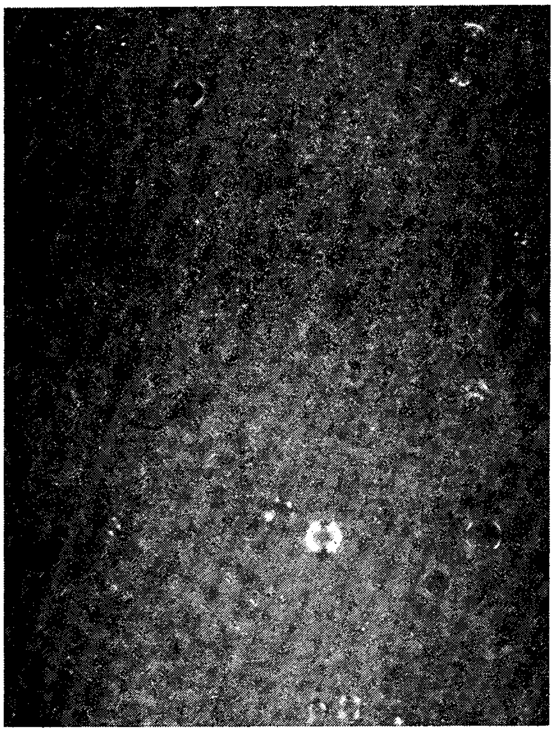
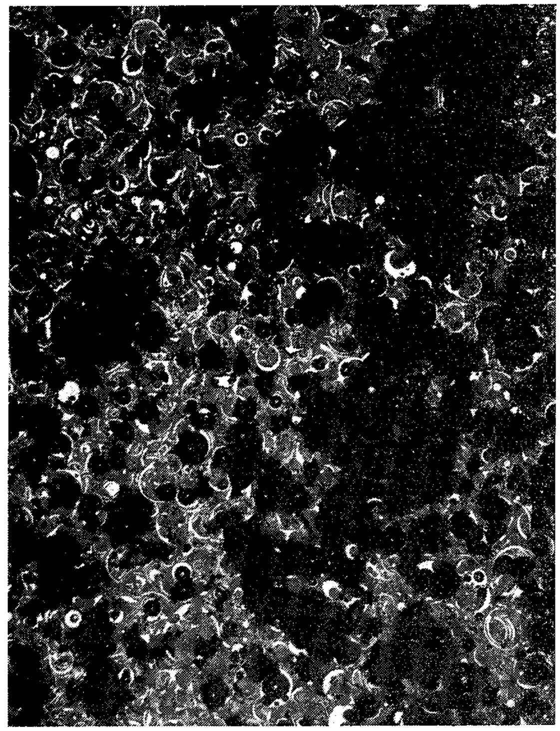


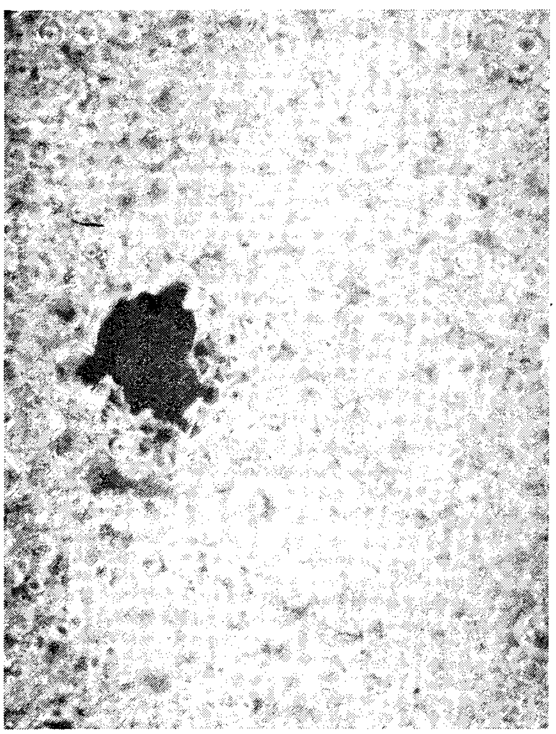
100X

HX501/A24X



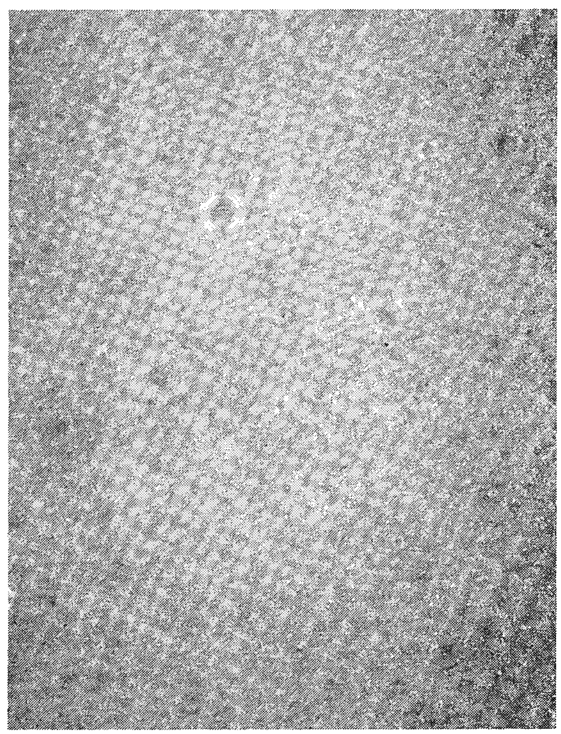
100X

HX501/Carbo-Spheres



100X

HX592/A24X



100X

Pro-Seal 828

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Figure 8. Core Microstructures After Humidity Exposure and One Thermal Cycle

d. Compressive Strength - The ultimate compressive strengths, F_{cu}, of fully cured core materials were determined at RT and 200°F, both as-fabricated and wet. The as-fabricated specimens were 2.90 x 0.50 x 0.14 in. The wet specimens were 2.90 x 0.50 x 0.07 in. and were exposed to 140°F/98% for 60 days. Testing was conducted in accordance with Federal Standard 406, Method 1021.

The as-fabricated compressive strengths are given in Table 10. These data reveal that:

1) The as-fabricated compressive strengths of the three developmental core materials were well below those for Pro-Seal 828.

2) In all cases, the 200°F strengths were less than the RT strengths.

3) Compressive strengths were significantly lower for the more porous sheet materials.

The wet compressive strengths and corresponding moisture contents are given in Table 11. Two important facts are revealed: 1) the HX501 cores were considerably stronger than their as-fabricated counterparts (see Table 10) because the sheets were less porous, and 2) the wet strengths of the HX501 cores at 200°F were approximately 40% greater than those of Pro-Seal 828. Wet compressive strengths of HX592/A24X were not determined due to difficulties in making good quality sheets of this material.

TABLE 10. COMPRESSIVE STRENGTHS OF AS-FABRICATED, FULLY CURED CORES

Specimen			Test Temperature (^oF)	F_{cu} (psi)
Material	Thickness (in.)	Width (in.)		
HX501/A24X (Sheet 1)	0.1432	0.5008	RT	10,500
	0.1413	0.5011		10,800
	0.1395	0.5004		10,760
	0.1377	0.5014		11,600
				(10,900)
	0.1380	0.5011	200	8,560
	0.1388	0.5015		8,730
	0.1429	0.5009		7,990
	0.1306	0.5003		8,950
				(8,560)
HX501/A24X (Sheet 2 - Less Porous than Sheet 1)	0.1410	0.5050	RT	10,830
	0.1450	0.5023		12,490
	0.1428	0.5032		11,830
				(11,700)
	0.1444	0.5010	200	10,020
	0.1440	0.5025		9,590
				(9,800)
HX501/Carbo-Spheres (Sheet 1 - Very Porous)	0.1240	0.5021	RT	5,960
	0.1215	0.5045		6,330
	0.1198	0.5040		6,920
	0.1184	0.5032		6,180
				(6,350)
	0.1182	0.5011	200	6,160
	0.1196	0.5038		5,990
	0.1212	0.5061		5,840
	0.1235	0.5008		5,900
				(5,970)
HX501/Carbo-Spheres (Sheet 2-Much Less Porous than Sheet 1)	0.1410	0.5036	RT	9,950
	0.1410	0.5030		10,010
	0.1424	0.5022		9,440
				(9,800)
	0.1413	0.5015	200	9,670
	0.1414	0.5035		7,440
	0.1415	0.5024		8,860
				(8,660)
HX592/A24X (Very Porous)	0.1431	0.5061	RT	8,220
	0.1430	0.5065		9,470
	0.1437	0.5057		9,600
	0.1436	0.5075		9,710
				(9,250)
	0.1443	0.5076	200	8,120
	0.1436	0.5077		8,390
	0.1450	0.5044		8,110
	0.1457	0.5064		7,860
				(8,120)

Note: Average valves are in parentheses.

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TABLE 10. (Concluded) COMPRESSIVE STRENGTHS OF AS-FABRICATED, FULLY CURED CORES

Specimen			Test Temperature (^oF)	F_{cu} (psi)
Material	Thickness (in.)	Width (in.)		
Pro-Seal 828 (Sheet 1)	0.1602	0.4927	RT	17,100
	0.1608	0.5034		17,230
	0.1614	0.5066		17,370
	0.1616	0.5075		16,160
				(16,970)
	0.1604	0.5119	200	12,850
	0.1603	0.5060		13,100
	0.1594	0.5064		13,380
	0.1595	0.5042		12,500
				(12,960)
Pro-Seal 828 (Sheet 2)	0.1375	0.5035	RT	13,260
	0.1410	0.5023		16,210
	0.1450	0.5028		15,090
				(14,850)
	0.1410	0.5025	200	12,220
	0.1375	0.5023		13,380
	0.1550	0.5010		10,960
				(12,190)

Note: Average valves are in parentheses.

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TABLE 11. COMPRESSIVE STRENGTHS OF WET, FULLY CURED CORES

Specimen			Moisture Content (%)	Test Temperature (^{o}F)	F_{cu} (psi)
Material	Thickness (in.)	Width (in.)			
HX501/A24X (Sheet 3)	0.0703	0.5043	3.29	RT	16,270
	0.0710	0.5028	3.33		18,120
	0.0694	0.5042	3.83		16,940
			(3.48)		(17,110)
	0.0705	0.5040	3.56	200	13,340
	0.0704	0.5017	3.28		13,360
	0.0703	0.5043	3.59		14,720
			(3.47)		(13,800)
HX501/Carbo-Spheres (Sheet 3)	0.0665	0.5050	5.07	RT	17,060
	0.0690	0.5036	5.37		18,040
			(5.22)		(17,550)
	0.0665	0.5050	5.07	200	14,000
	0.0690	0.5036	5.37		11,870
			(5.22)		(12,930)
Pro-Seal 828 (Sheet 3)	0.0780	0.5055	6.42	RT	16,230
	0.0762	0.5022	6.49		16,940
	0.0713	0.5094	6.13		17,450
			(6.34)		(16,870)
	0.0738	0.5053	6.33	200	9,790
	0.0825	0.5057	6.14		8,720
	0.0793	0.5005	6.56		10,180
			(6.34)		(9,560)

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Notes:

1) Specimens were exposed to 140°F/98% RH for 60 days.
2) Average values are in parentheses.

SECTION IV

SANDWICH PANELS

B-staged sheets of each of the three syntactic core materials were co-cured between two 3-ply graphite/epoxy skins. The sandwiched panels were ultrasonically inspected and found to have no bonding defects. Radiographic examinations revealed that the cores were relatively nonporous. These panels were then used to determine moisture pickup characteristics (140°F/92% RH), flatwise tensile strengths, short beam shear strengths, and impact resistance.

The tensile and shear strengths were determined at both RT and 200°F for the following conditions: 1) as-fabricated, 2) moisture saturated, and 3) moisture saturated and thermal cycled 22 times between -67° and 200°F. All impact testing was done at RT on as-fabricated panels. The results obtained were compared with those for Pro-Seal 828.

1. FABRICATION - Two 12 x 13 in. sandwich panels were fabricated for each of the three core materials. These panels consisted of 0.07 in. B-staged core sheet, cocured between two 3-ply graphite/epoxy skins. The ply layup was:

outer ∿ +45° woven T300

middle ∿ 0° AS tape

inner ∿ -45° woven T300

The matrix was 3501-6 epoxy.

The sandwiched core panels were cured in accordance with the cycles given in Table 6. The autoclave layup is shown in Figure 9.

The panels were ultrasonically inspected using a through-transmission reflector method run at 2,250 Hz. The C-scans revealed no unbonds and relatively uniform densities.

2. EVALUATION - The sandwiched core panels were cut into test specimens, using either a diamond cutoff wheel or a diamond core cutter (circular specimens). Visual examination of cut edges revealed that these cores were generally less porous than the fully-cured cores of Section III.3. The specimens were used to determine: 1) moisture pickup data; 2) flatwise tensile and short beam shear strengths (RT and 200°F - as-fabricated, wet, and wet after thermal cycling); and 3) impact resistance.

a. Moisture Pickup - Moisture pickup data were obtained for each of the following exposures:

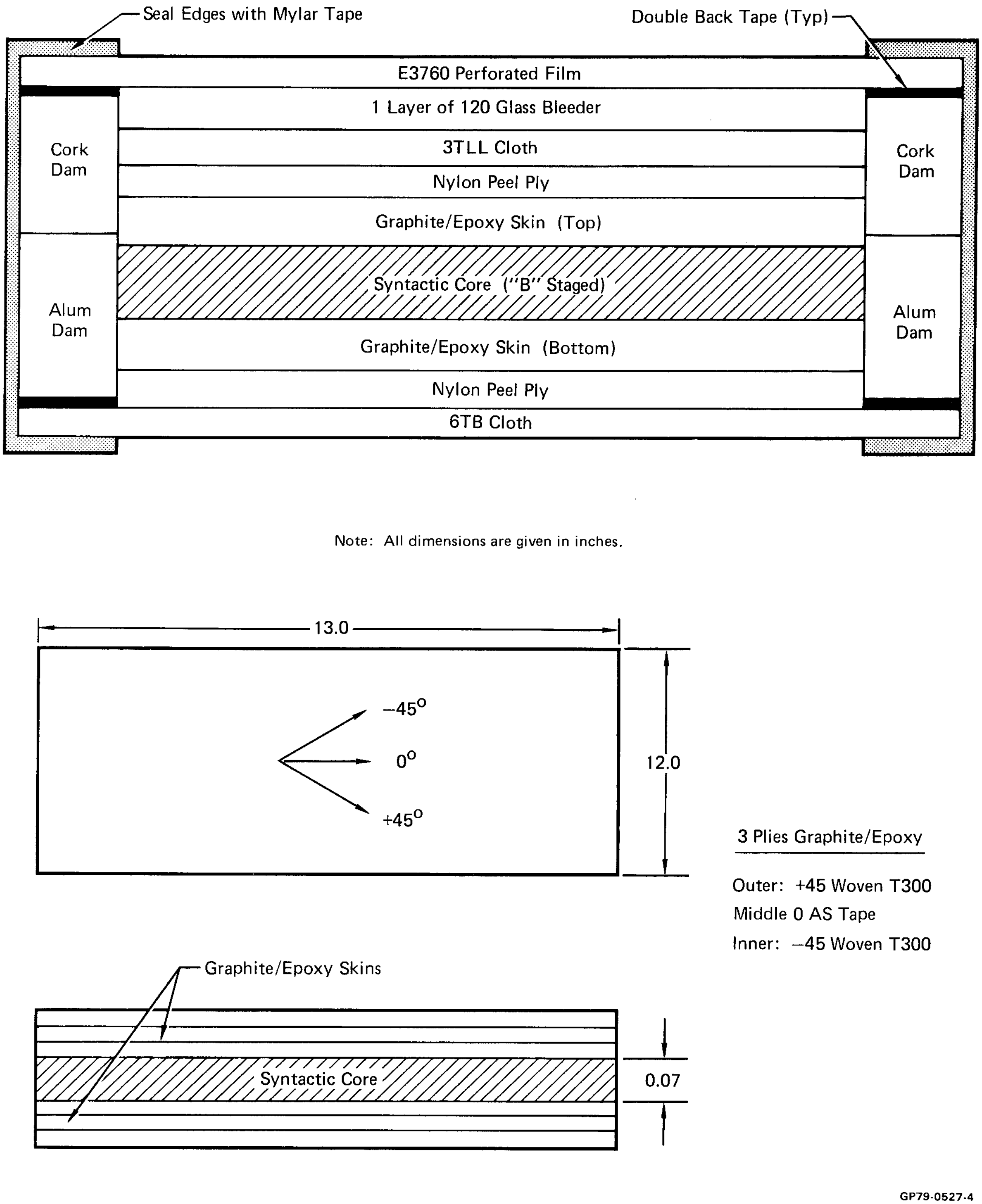

Figure 9. Autoclave Layup for Sandwiched Syntactic Core

1) 72 days of humidity (140°F/92% RH) only, and

2) 72 days of humidity (140°F/92% RH) with twice weekly thermal cycling (10 minutes at -67°F followed by 10 minutes at 200°F).

Eight flatwise tension specimens (1.92 in. dia. x 0.13 in.) and eight short beam shear specimens (1.0 x 0.25 x 0.13 in.) of each core material were used for each type of exposure. The edges of the flatwise tension specimens were sealed against moisture with lead foil tape. The edges of the short beam shear specimens were not sealed. All specimens were oven dried at 275 ± 10°F for 24 hours and weighed to the nearest ±0.001 g prior to exposure.

Test procedures were similar to those used for the bare core (see III.3.b. and c.). However, instead of weighing test specimens in pairs, all eight specimens of each type were weighed and all of these weights were averaged. Also, the holds at -67° and 200°F were for 10 rather than 30 minutes.

The moisture pickup data (without thermal cycling) for the flatwise tension and short beam shear sandwiched core specimens are plotted in Figures 10 and 11, respectively. Since the core edges of the flatwise tension specimens were sealed against moisture, Figure 10 was generated by moisture pickup in the graphite/epoxy skins. By contrast, in the short beam shear specimens, moisture was readily absorbed by the unsealed edges. Consequently, by the seventh day of exposure, data began to show significant differences in moisture pickup.

The moisture pickup data (with thermal cycling) for the flatwise tension and short beam shear specimens are plotted in Figures 12 and 13, respectively. The same trends are evident in these plots as are evident in Figures 10 and 11.

The moisture contents of various specimens at the end of the 72 day exposures are given in Table 12. With one exception, the thermal cycled specimens exhibited moisture contents 0.1 to 0.5% by wt. greater than those which were exposed to high humidity only. It is to be noted that these values are based on the total specimen weight, i.e., skin plus core.

b. Flatwise Tension - The flatwise tensile strengths of the three types of sandwiched core were determined at RT and 200°F for three conditions:

1) As-fabricated

2) Wet (see Table 12 for moisture contents)

3) Wet and thermal cycled (see Table 12 for moisture contents)

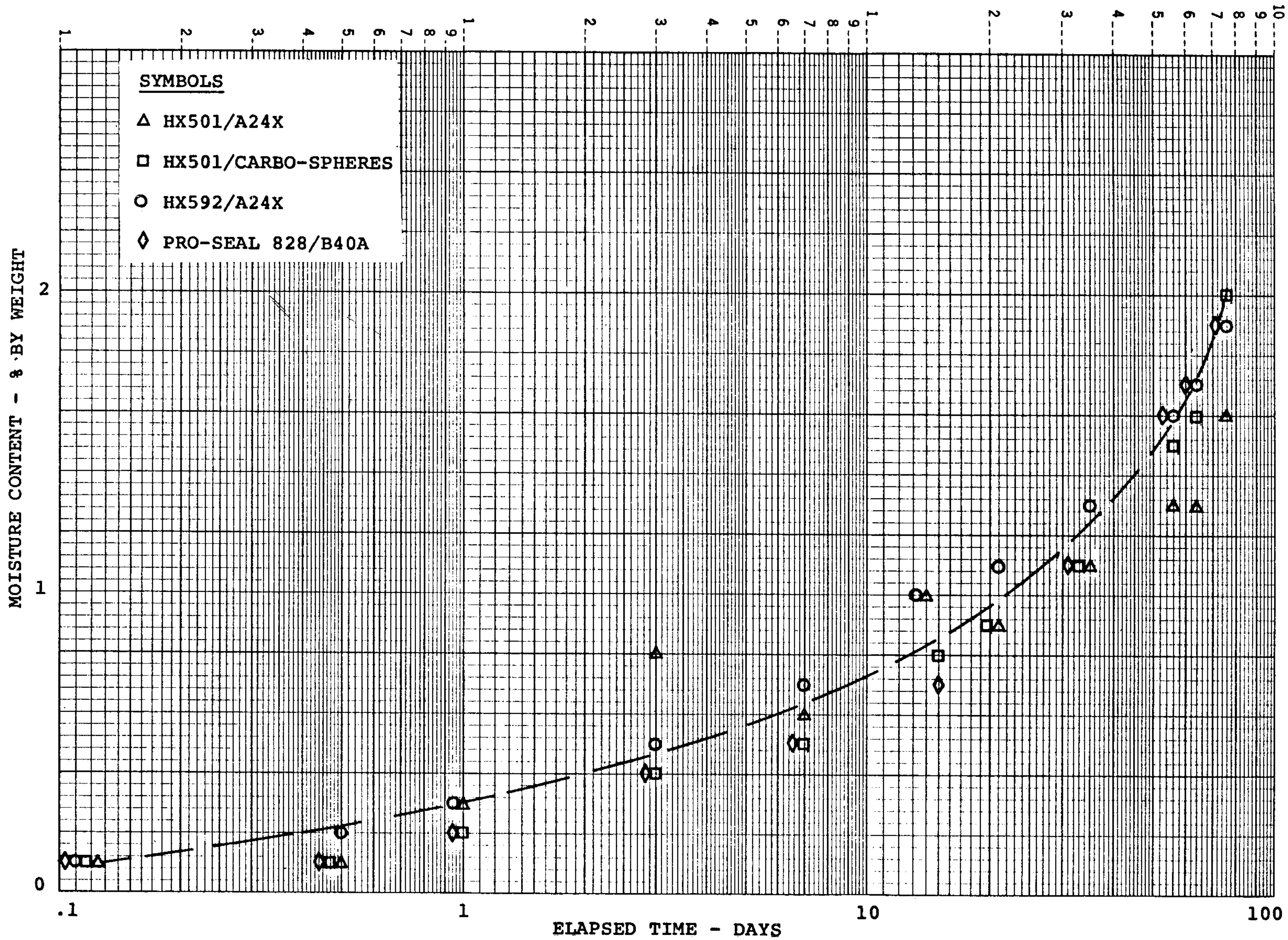

Figure 10. Moisture Pickup Versus Time at 140°F/92% RH for Flatwise Tension Specimens

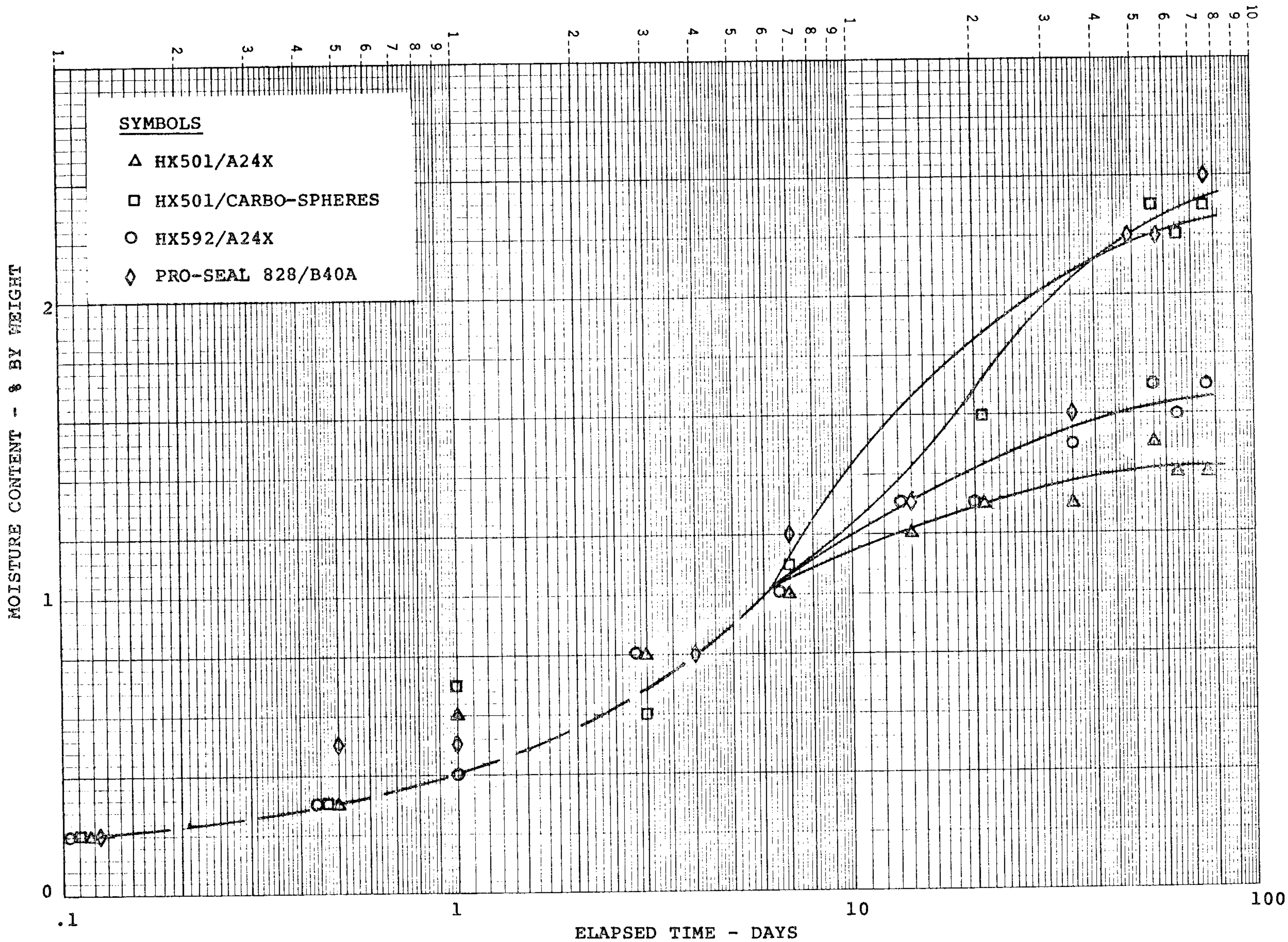

Figure 11. Moisture Pickup Versus Time at 140°F/92% RH for Short Beam Shear Specimens

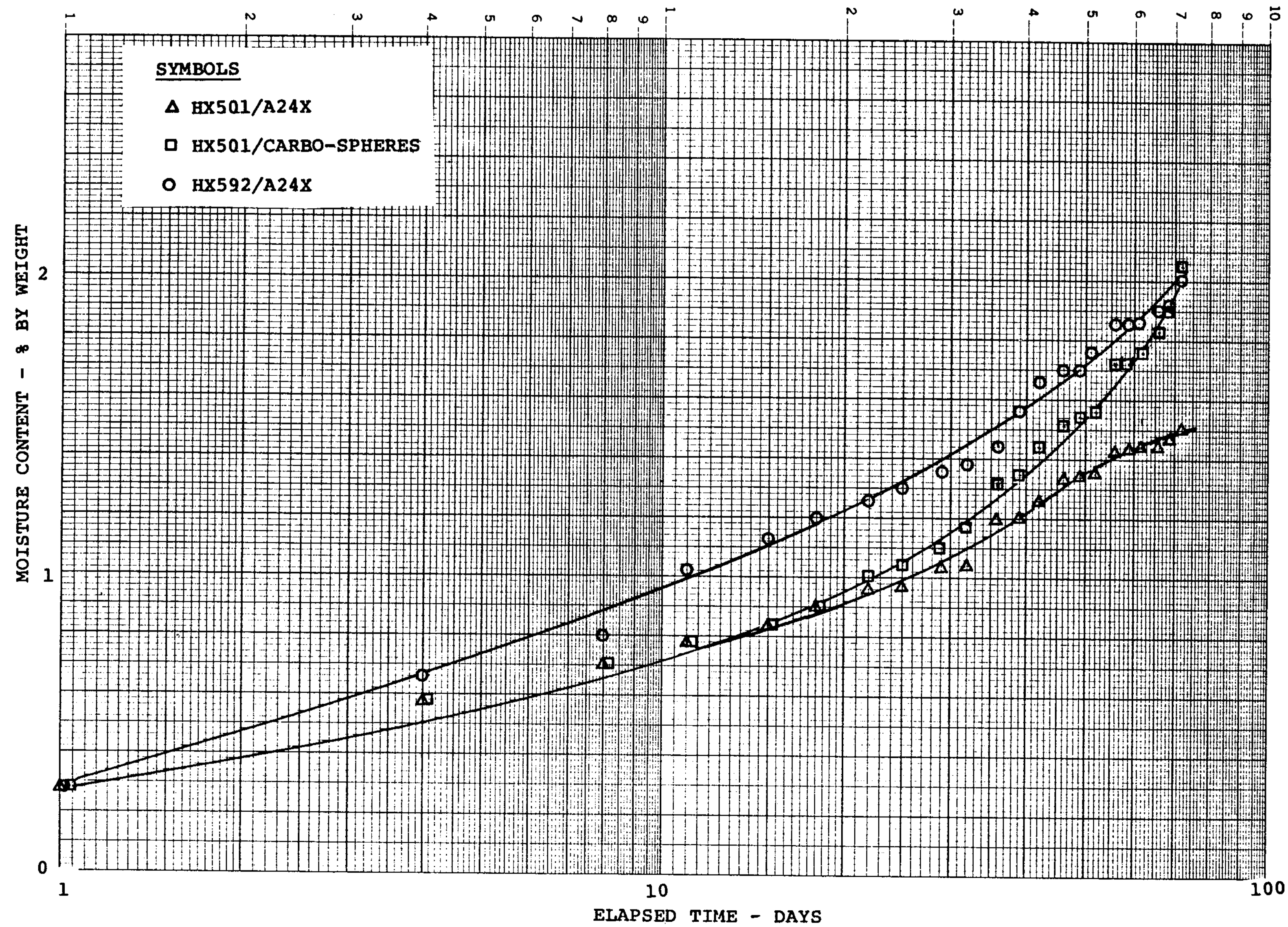

Figure 12. Moisture Pickup Versus Time at 140°F/92% RH with Twice Weekly Thermal Cycling for Flatwise Tension Specimens

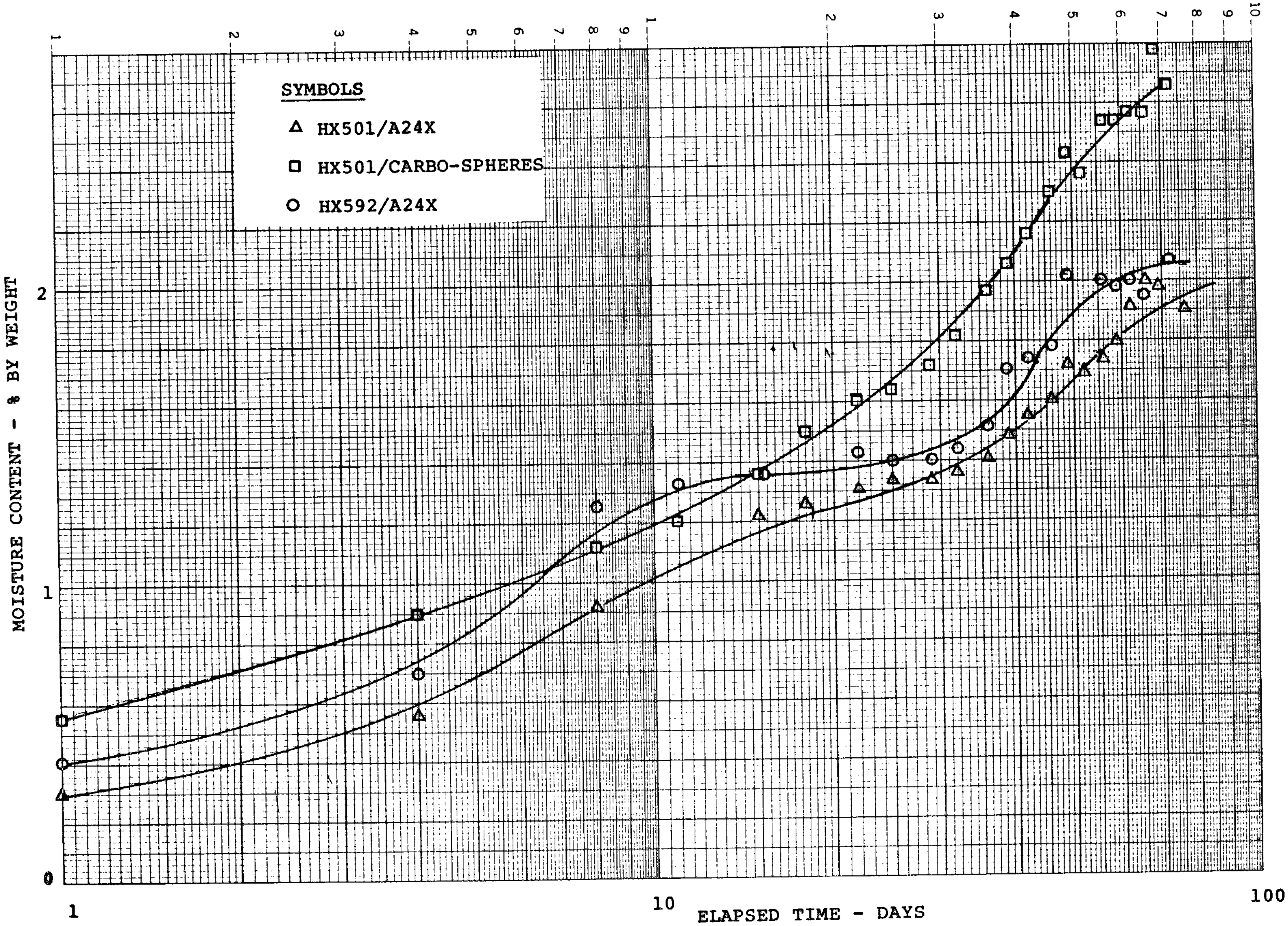

Figure 13. Moisture Pickup Versus Time at 140°F/92% RH with Twice Weekly Thermal Cycling for Short Beam Shear Specimens

TABLE 12. MOISTURE CONTENTS OF SANDWICHED CORE SPECIMENS EXPOSED TO 140°F/92% RH FOR 72 DAYS

Core Material	Moisture Content (% by Wt)			
	Humidity Only		Humidity Plus Thermal Cycling	
	FWT	SBS	FWT	SBS
HX501/A24X	1.6	1.4	1.5	1.7
HX501/Carbo-Spheres	2.0	2.2	2.1	2.7
HX592/A24X	1.9	1.7	2.0	2.1

Note: FWT = Flatwise Tension
SBS = Short Beam Shear

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Twenty-four specimens of each core material, eight for each condition, were adhesively bonded to aluminum blocks, individually installed in a test jig (see Figure 14), and loaded in tension at a rate of 1,000 lb/min. Strengths were calculated by dividing the loads at failure by 2.89 in^2, the cross-sectional area.

The flatwise tension strengths, F_{tu}, are tabulated in Table 13. The mode of failure is given to the right of each value. An example of each mode of failure is shown in Figure 15.

Table 13 reveals a significant decrease in the wet strengths of Pro-Seal 828 core specimens at 200°F. This decrease is not evident in HX501/A24X core and is less pronounced for HX501/Carbo-Spheres core. Also, the mode of failure for wet Pro-Seal 828 was core and core-to-skin failures at 200°F, rather than the skin delamination experienced at RT. By contrast, the mode of failure for wet HX501/A24X remained predominantly one of skin delamination, indicating that the core remained stronger in tension than the 3501-6 bond between the graphite plies.

The HX592/A24X is a brittle material, as noted by microcracks in the as-fabricated core and the texture of the failed surface (see Figure 15). Nevertheless, with the exception of two very low values (940 and 740 psi), the flatwise tensile strengths of this core material were on a par with those for the epoxy resin systems. The HX592/A24X was the only core which showed greater RT strengths when wet than as-fabricated. Evidently, the moisture plasticized the bis-maleimide resin and improved its toughness.

c. <u>Short Beam Shear</u> - The short beam shear strengths of the three types of sandwiched core were determined for the same conditions used to determine flatwise tensile strengths. Specimens were installed in a test jig (see Figure 16) and loaded to failure at a constant head travel rate of 0.05 in./min. The span was 0.72 in. in all cases.

Shear strengths, F_{ty}, were calculated from the following equation:

$$F_{ty} = \frac{0.75P}{W} \left(\frac{T_t + T_c}{T_t^2 + T_t T_c + T_c^2} \right)$$

where P = ultimate load, lb.

W = specimen width, in.

T_c = core thickness, in.

T_t = total specimen thickness (core plus skins), in.

The short beam shear strengths are tabulated in Table 14. Typical failed specimens are shown in Figure 17.

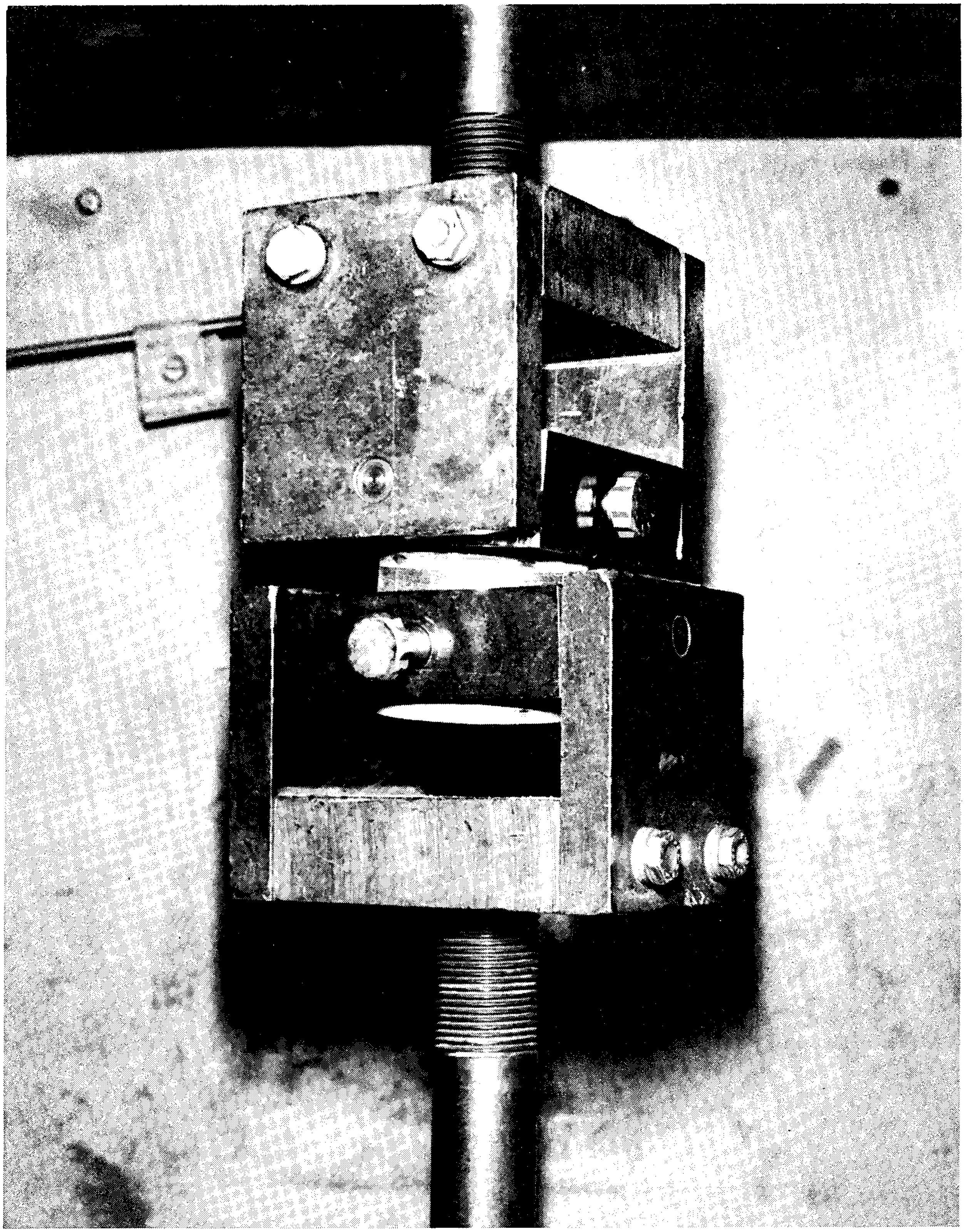

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Figure 14. Flatwise Tension Test Setup

TABLE 13. FLATWISE TENSILE STRENGTHS OF SANDWICHED CORES

Specimen		Test Temperature (^oF)	F_{tu}		
Core Material	Diameter (in.)		As-Fabricated (psi)	Wet* (psi)	Thermal Cycled** (psi)
HX501/A24X	1.92	RT	1,739 I 2,020D 2,210D 2,120D (2,020)	1,590D 1,780D 1,910D 1,590D (1,720)	1,630D 1,530D 1,250D 1,670D (1,520)
	1.92	200	1,400D 1,780D 2,270D 1,900D (1,840)	1,840D 1,700 I 1,660C 1,620D (1,710)	1,470C 1,520D 1,530D 1,600D (1,530)
HX501/Carbo-Spheres	1.92	RT	2,180D 2,020 I 2,300D 2,280 I (2,200)	1,620D 2,320D 2,500 I/C 2,000 I (2,110)	1,970D 2,020D 1,900D 1,680D (1,890)
	1.92	200	2,180 I 1,970 I 2,510 I 2,040 I (2,180)	1,660 I 2,040 I/C 1,210D 1,710D (1,660)	1,850D 1,700 I 1,900 I 1,890 I (1,840)
HX592/A24X	1.92	RT	1,700 I 1,720 I 1,730 I 1,770 I (1,730)	2,530C 2,590 I 2,440 I/C 2,150 I (2,430)	1,750C 2,210 I/C 940 I/C+ 1,850 I (1,940)
	1.92	200	1,990 I 1,750 I 1,990 I 1,770 I (1,880)	1,450 I/C 1,560C 1,870 I/C 1,850C (1,680)	740C+ 1,520C 1,730C 1,870 I/C (1,710)
Pro-Seal 828	1.92	RT	2,240 I 2,150 I 2,040D 2,150D (2,150)	1,910D 1,890D 1,970D 2,250D (2,000)	2,260C 1,570D 1,970D 1,730D (1,880)
	1.92	200	1,890D 2,020D 2,150D 1,930D (2,000)	1,670 I 1,390C 1,550C 1,510 I/C (1,530)	1,120C 1,070 I/C 1,430C 1,290 I (1,230)

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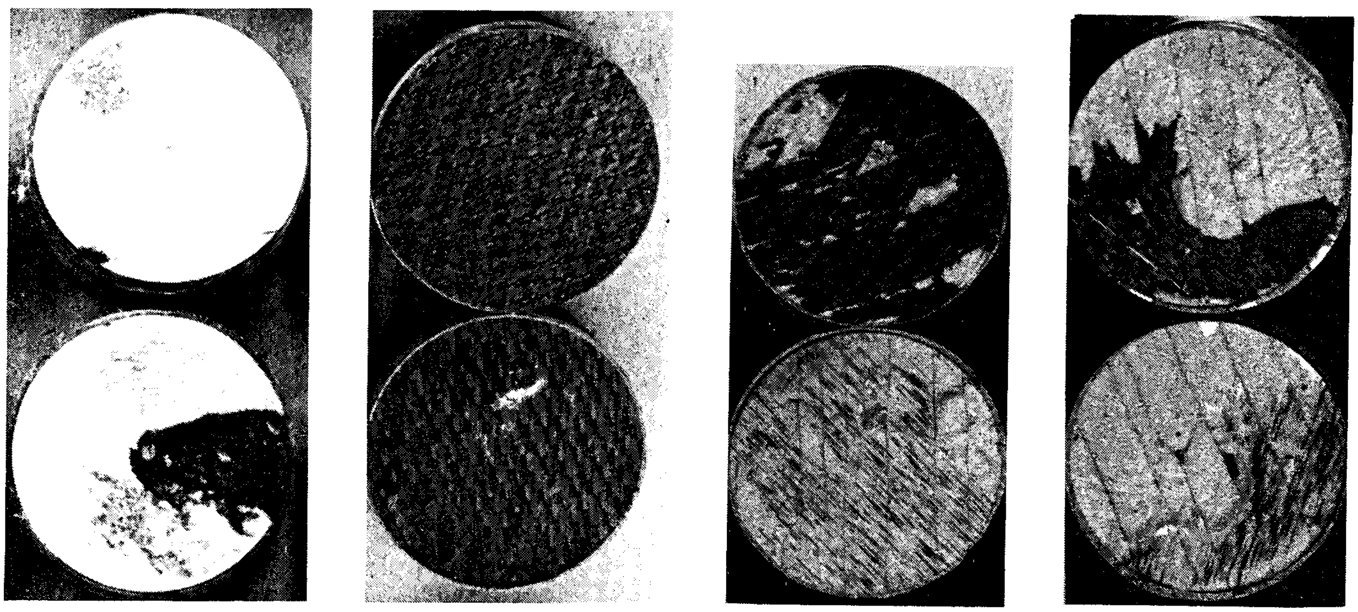
*Exposed to 140^oF/92% RH for 72 days.

**Exposed to 140^oF/92% RH for 72 days with twice weekly thermal cycling (10 min at −67^oF followed by 10 min at 200^oF).

+Not used in average

Notes:

1) Average values are in parentheses.
2) Mode of failure is indicated to the right of each strength value:
   - C = Cohesive (Core)
   - D = Delamination (Skin)
   - I = Interfacial (Core-to-Skin)



Cohesive (Core)
HX501/A24X

Delamination (Skin)
HX501/A24X

Interfacial (Core-to-Skin)
HX592/A24X

Interfacial/Cohesive
HX592/A24X

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Figure 15. Examples of Flatwise Tension Failure Modes

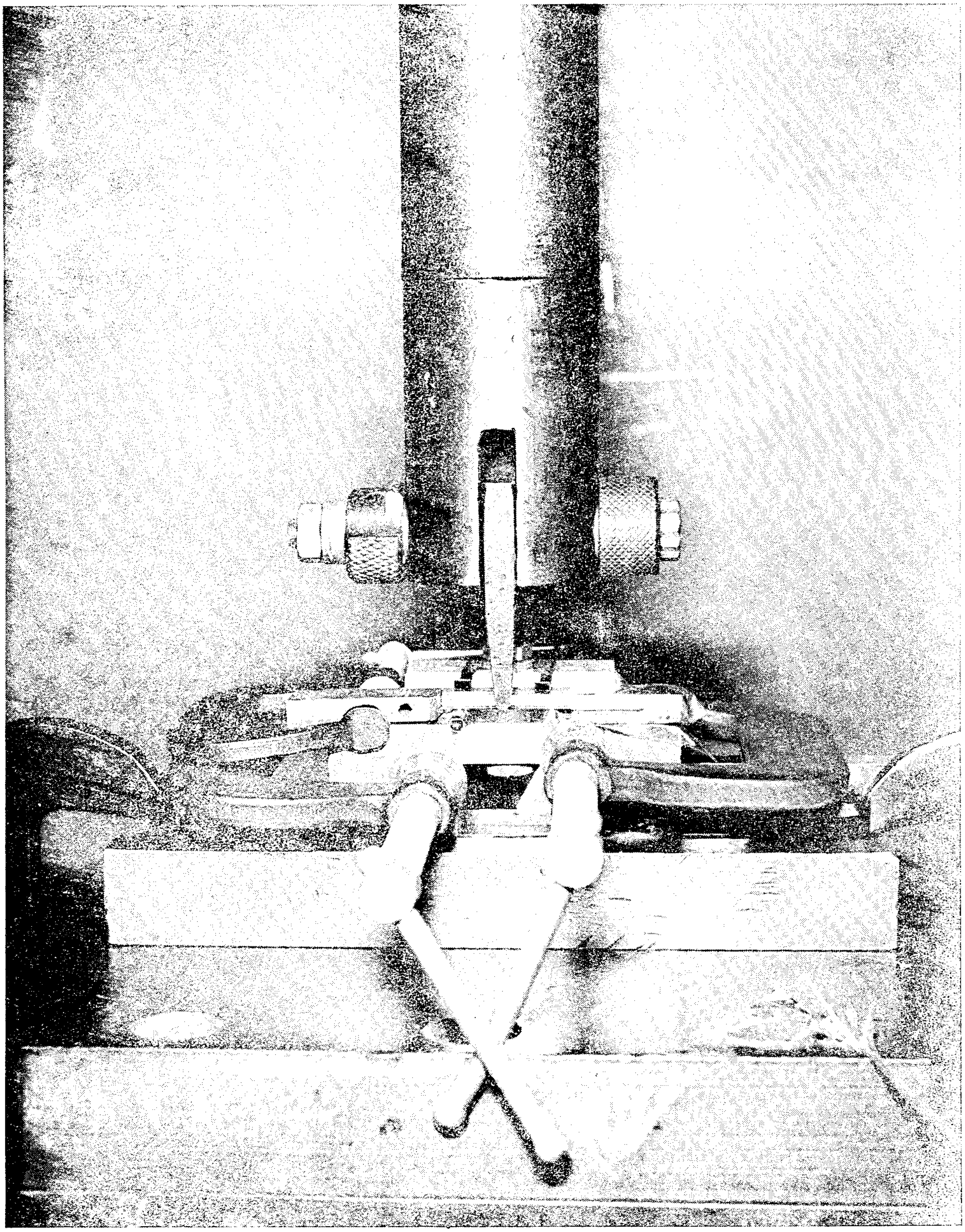

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Figure 16. Short Beam Shear Test Setup

TABLE 14. SHORT BEAM SHEAR STRENGTHS OF SANDWICHED CORES

Specimen		Test Temperature (^{o}F)	F_{ty}		
Core Material	Span (in.)		As-Fabricated (psi)	Wet* (psi)	Thermal Cycled** (psi)
HX501/A24X	0.72	RT	3,830 4,010 4,100 3,690 (3,910)	2,200 2,560 2,730 2,040 (2,380)	2,670 2,050 3,100 2,170 (2,500)
	0.72	200	3,810 3,740 3,230 3,470 (3,590)	1,870 1,850 1,680 1,820 (1,810)	1,890 1,670 1,710 1,550 (1,710)
HX501/Carbo-Spheres	0.72	RT	4,330 3,530 3,200 4,880 (3,990)	2,960 2,900 1,770 2,130 (2,440)	1,930 2,830 2,650 2,440 (2,460)
	0.72	200	1,930 2,380 2,170 2,050 (2,130)	2,180 2,080 1,710 1,700 (1,920)	1,680 1,390 2,150 1,810 (1,760)
HX592/A24X	0.72	RT	1,620 1,900 1,720 1,800 (1,760)	1,650 1,450 1,620 1,790 (1,630)	1,670 1,760 1,680 2,060 (1,790)
	0.72	200	1,470 1,610 1,640 1,520 (1,560)	1,170 1,160 1,290 860 (1,120)	1,380 1,480 1,450 1,430 (1,440)
Pro-Seal 828	0.72	RT	3,070 4,060 4,100 4,430 (3,920)	1,820 1,870 1,970 1,490 (1,790)	2,280 2,060 1,760 1,550 (1,910)
	0.72	200	4,010 3,470 3,110 3,410 (3,500)	1,490 1,530 1,120 1,510 (1,410)	1,230 1,340 1,270 1,250 (1,270)

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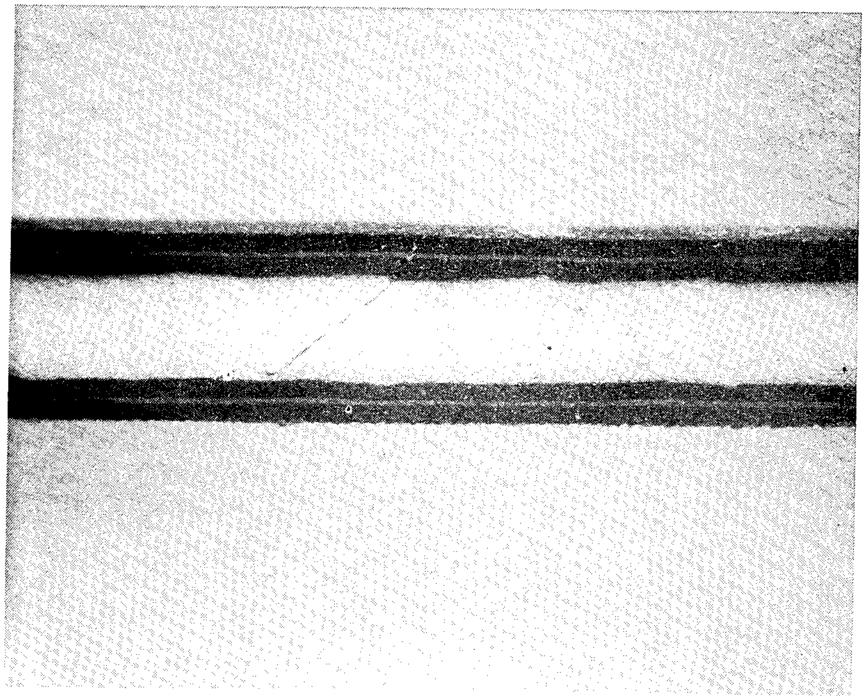
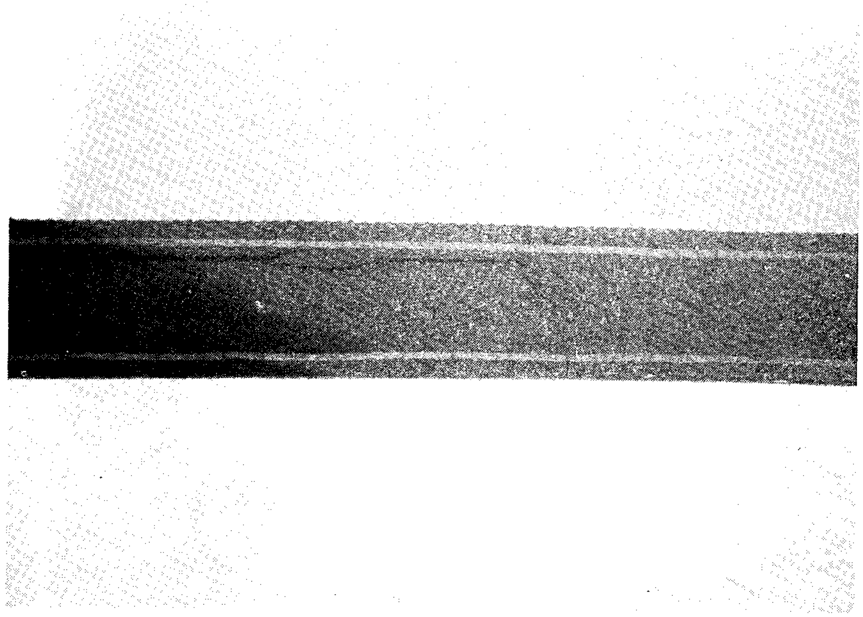
*Exposed to 140^{o}F/92% RH for 72 days.

**Exposed to 140^{o}F/92% RH for 72 days with twice weekly thermal cycling (10 min at –67^{o}F followed by 10 min at 200^{o}F.

Note: Average values are in parentheses.



HX501/A24X (Dry, $200^{\circ}F$) 7X



HX501/Carbo-Spheres (Dry, $200^{\circ}F$) 7X

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Figure 17. Typical Failed Short Beam Shear Specimens

The average strengths at 200°F for a given condition were less than those at RT. This was expected, as the same trend had been noted in both the flatwise tensile and core compressive strengths.

The effect of moisture in reducing shear strength is very evident in all of the epoxy-based core materials. The bis-maleimide resin system exhibited similar strengths wet and as-fabricated, but its shear strengths were less in all categories than those for the epoxy resin systems.

Finally, the wet shear strengths of the two HX501 resin systems are seen to be significantly greater than those for Pro-Seal 828. The HX501/A24X specimens, for example, exhibited 28 to 35% greater average wet strengths than Pro-Seal 828.

d. Impact Resistance - Four 6 x 6 x 0.13 in. panels of each core material were tested on the Gardner Impact Tester, Figure 18. One panel of each type was subjected to 1, 2, 4, and 8 ft-lb. Each panel was placed in a metal frame which supported a 1/2-in. wide strip around its perimeter (not shown in Figure 18). The 0.5 in. diameter impactor was placed on its center, and the 2-lb weight was dropped from the appropriate height. Each panel was visually and ultrasonically inspected for damage. Each panel was also sectioned through its center of impact and the cross sections were photographed at a magnification of 3.5X.

The impact resistance is summarized in Table 15. The C-scans, presented in Appendix A, and the photomacrographs, presented in Appendix B, reveal that only the panel containing HX501/A24X core showed no disbonding or core damage as the result of a 1 ft-lb impact. At an impact energy of 2 ft-lb, all panels exhibited significant damage and, at 8 ft-lb, all panels were penetrated as shown in Figure 19.

The HX592/A24X core panels were more susceptible to impact damage than the others. This further illustrates the brittleness of the bis-maleimide resin.

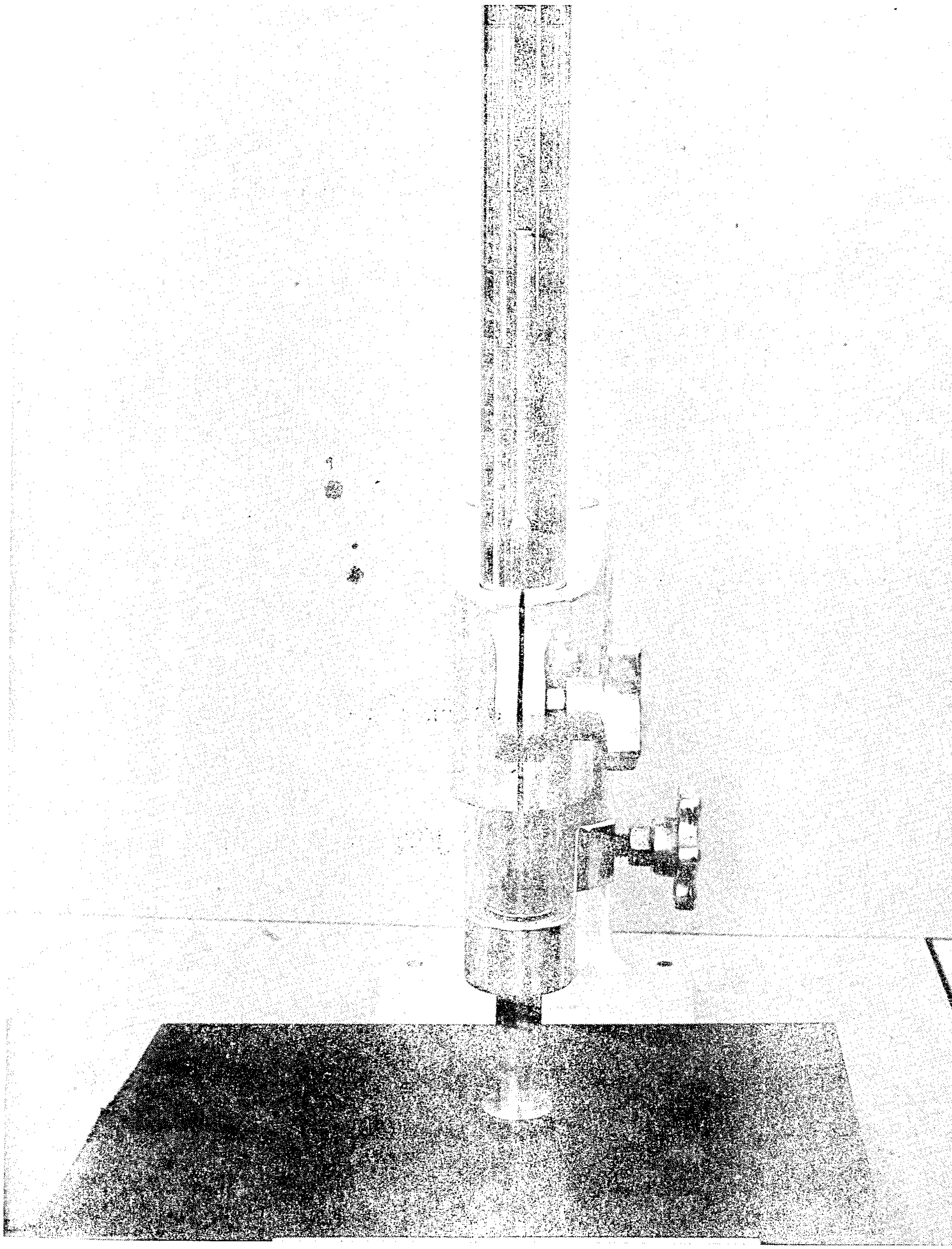

Figure 18. Gardner Impact Tester

TABLE 15. IMPACT RESISTANCE OF SANDWICH PANELS

Core Designation	Damage for Impact Energy of:			
	1 (ft-lb)	2 (ft-lb)	4 (ft-lb)	8 (ft-lb)
HX501/A24X	None	D	D	D + P
HX501/Carbo-Spheres	D	D	D	D + P
HX592/A24X	D	D	D	D + P
Pro-Seal 828	D	D	D	D + P

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D = Disbonding
P = Penetration
Impactor tip: 1/2 in. diameter hemisphere

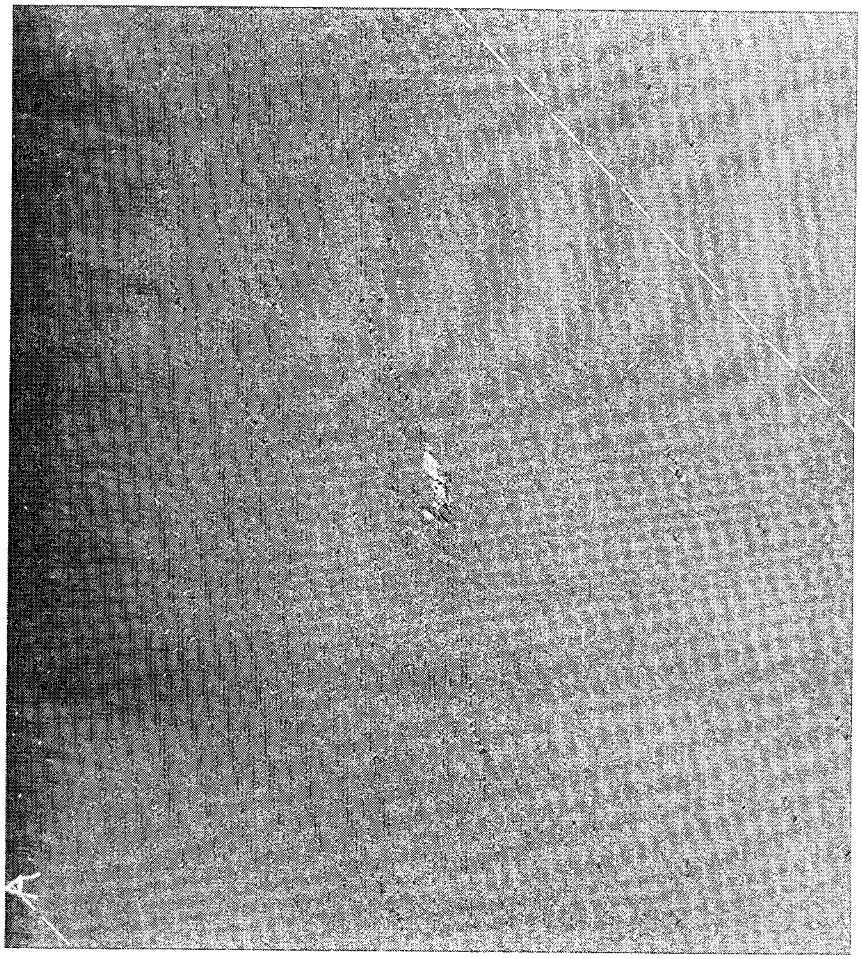

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Figure 19. Back Surface of Sandwiched HX501/A24X Core After 8 Ft-Lb Impact

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

Selected syntactic core properties are compared in Table 16. The HX501/A24X and HX592/A24X syntactic core materials had saturation moisture contents about 50% less than Pro-Seal 828. For HX501/A24X, this lower water pickup led to significantly greater 200°F wet strengths. Processing variations, however, failed to produce a nonporous HX592/A24X core. Consequently, the strengths obtained for this material were generally lower than those for the other materials.

Due to the high moisture pickup of Carbo-Spheres, HX501/Carbo-Spheres had even a higher saturation moisture content than Pro-Seal 828. However, as the HX501 resin had a low moisture pickup, the wet strengths of this core were similar to those for HX501/A24X.

The densities of the fully cured HX501/A24X and HX592/A24X cores (46.8 and 42.7 lb/ft^3, respectively) were only slightly less than that for Pro-Seal 828 (48.0 lb/ft^3). The HX501/Carbo-Spheres had a density of 60.5 lb/ft^3, due to many of the spheres being broken during processing.

All of the sandwich panels exhibited low impact resistance showing significant damage for an impact energy of 2 ft/lb. The sandwiched HX501/A24X was slightly more impact resistant than the sandwiched Pro-Seal 828. The HX592/A24X core produced the least resistant panels.

Considering processability, density, moisture pickup, dry and wet strengths, and impact resistance, HX501/A24X is superior to Pro-Seal 828 as well as the other two materials investigated on this program.

It is recommended that future work on syntactic core materials concentrate on improving the impact resistance. As a goal, the resistance should match that of solid graphite/epoxy laminates.

TABLE 16. COMPARISON OF SELECTED SYNTACTIC CORE PROPERTIES

Property	Units	Value For			
		HX501/A24X	HX501/C-S	HX592/A24X	Pro-Seal 828
Core					
Density	lb/ft^3	46.8	60.5	42.7	48.0
Moisture Content (Saturated at $-140^{o}F$/92% RH)	% by Wt	1.7	5.0	2.1	3.3
Wet Compressive Strength					
– @ RT	psi	17,110	17,550	*	16,870
– @ $200^{o}F$	psi	13,800	12,930	*	9,560
Sandwiched Core					
Wet Short Beam Shear Strength					
– @ RT	psi	2,380	2,440	1,630	1,790
– @ $200^{o}F$	psi	1,810	1,920	1,120	1,410
Impact Resistance					
– @ 1 ft-lb	–	No Damage	Damage	Damage	Damage
– @ 2 ft-lb	–	Damage	Damage	Damage	Damage

*Not measured

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APPENDIX A

C-SCANS OF SANDWICHED CORE PANELS AFTER 1 FT-LB IMPACT

Ultrasonic C-scans of 6 x 6 x 0.13 in. sandwiched core panels after impact testing at 1 ft-lb are shown in Figures A-1 through A-4. C-scans were obtained using a through-transmission, reflector plate method at a frequency of 2,250 Hz.

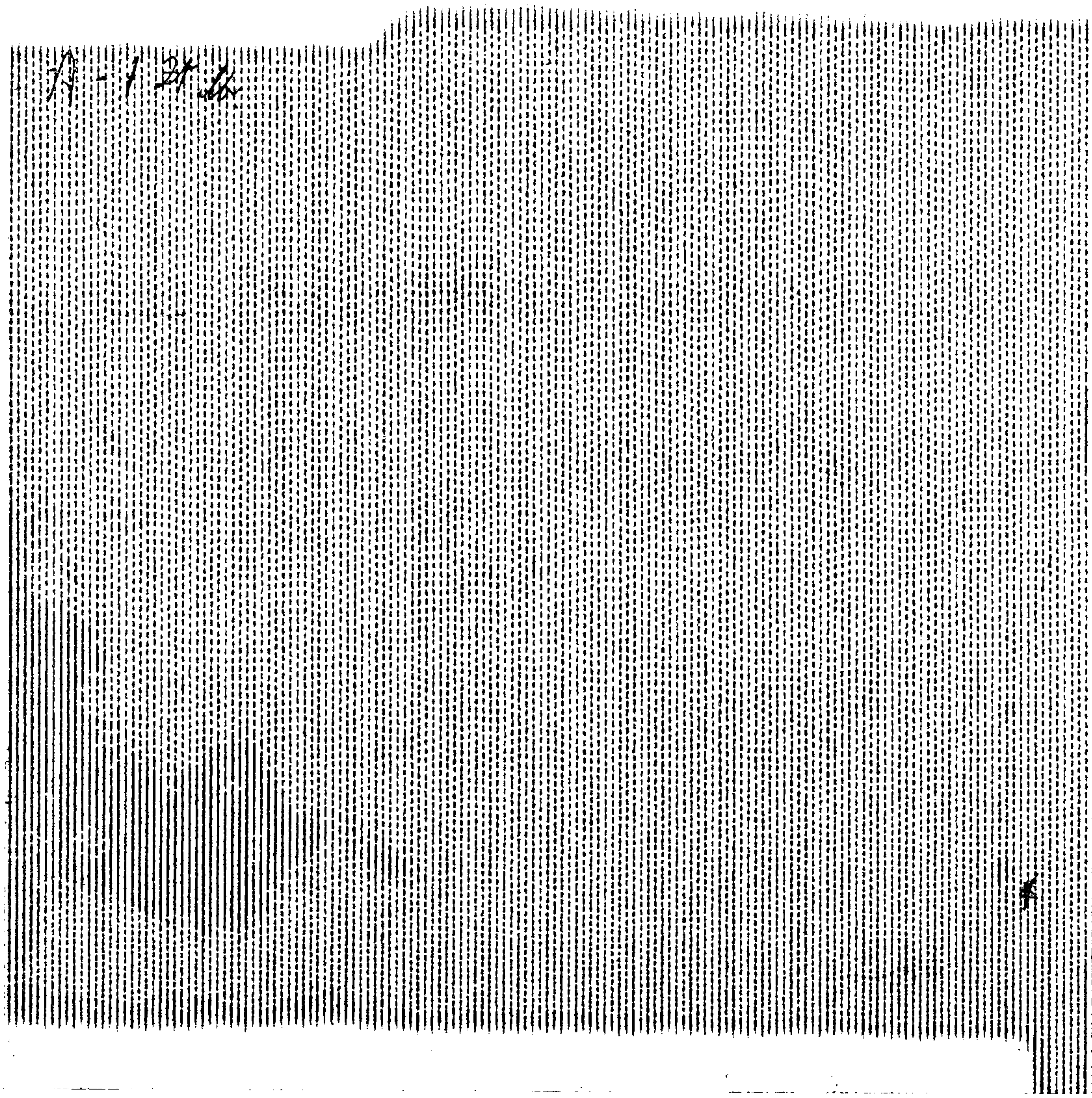

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Figure A-1. C-Scan of Sandwiched HX501/A24X Core After 1 Ft-Lb Impact

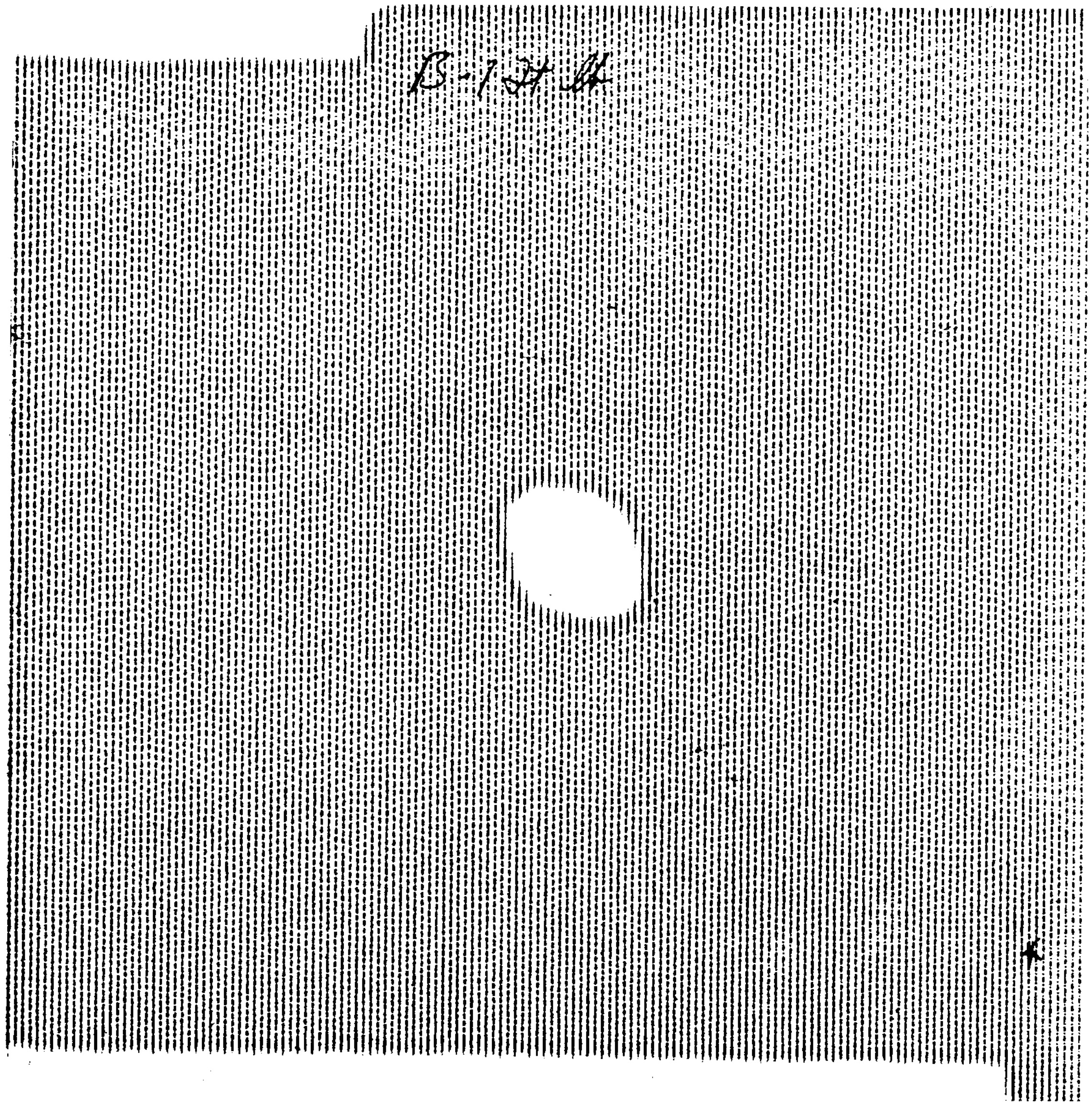

Figure A-2. C-Scan of Sandwiched HX501/Carbo-Sphere Core After 1 Ft-Lb Impact

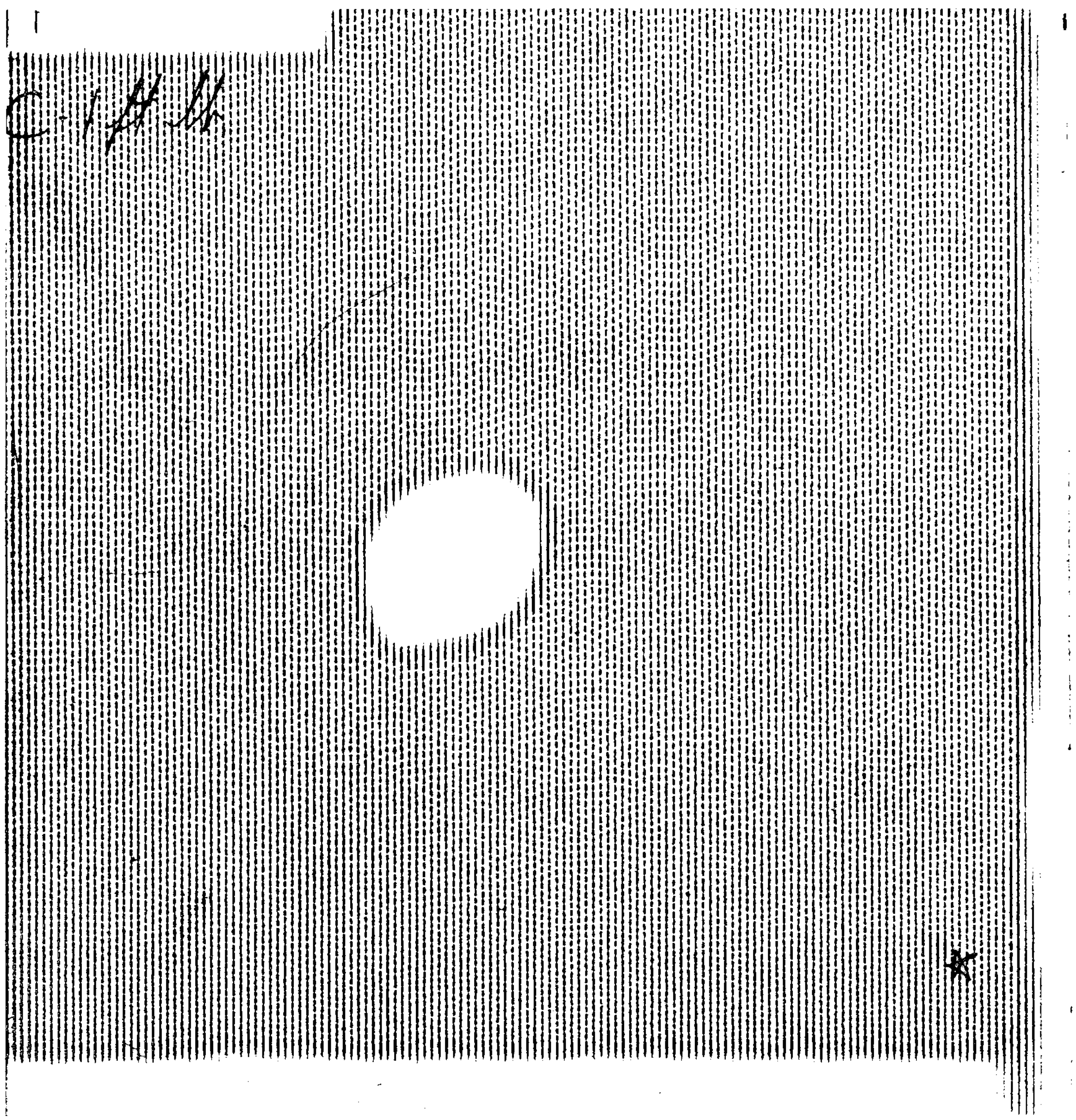

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Figure A-3. C-Scan of Sandwiched HX592/A24X Core After 1 Ft-Lb Impact

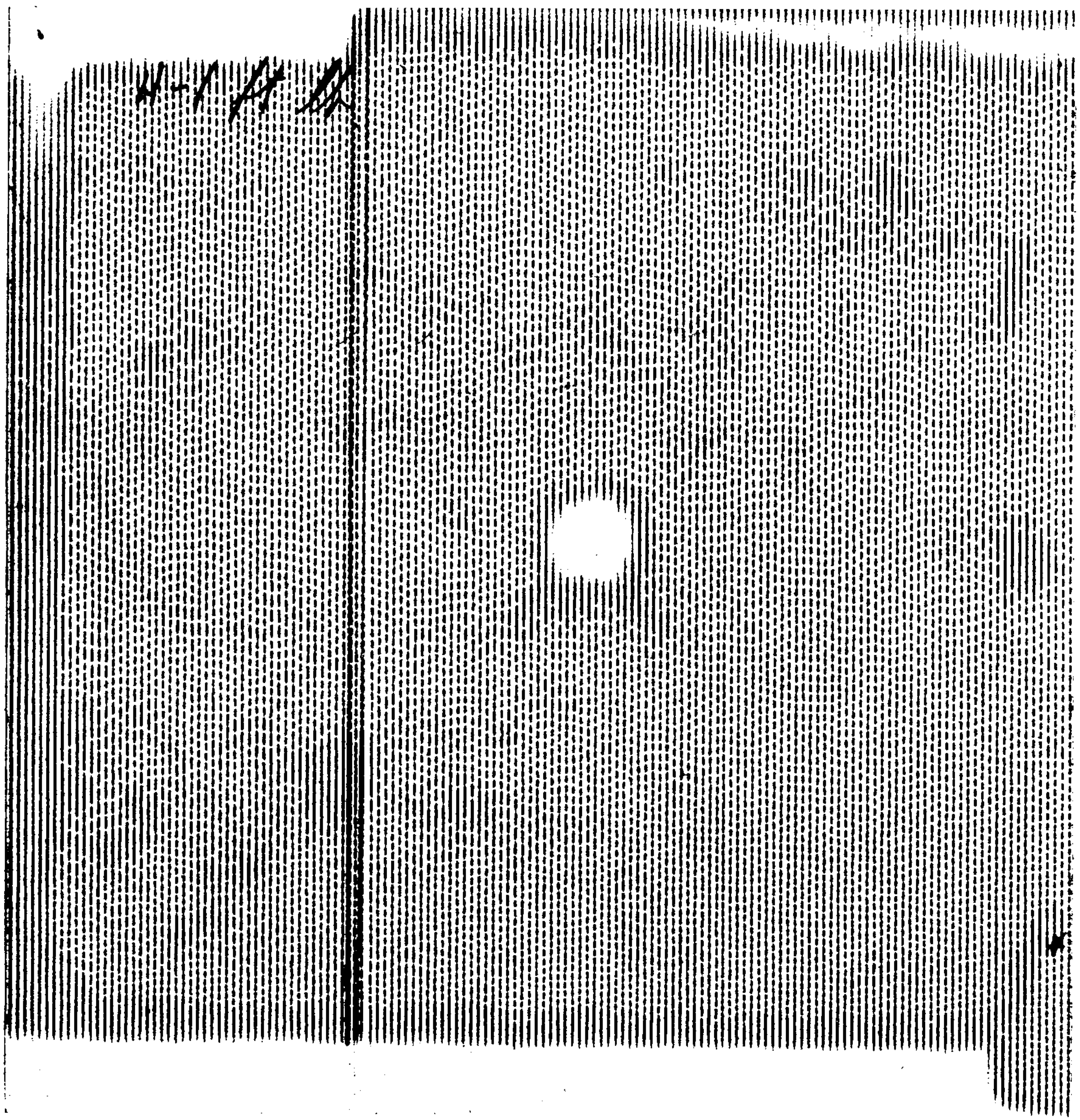

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Figure A-4. C-Scan of Sandwiched Pro-Seal 828 Core After 1 Ft-Lb Impact

APPENDIX B

PHOTOMACROGRAPHS OF IMPACTED SANDWICHED CORE PANELS

Photomacrographs of cross sections of 6 x 6 x 0.13 in. sandwiched core panels after impact testing are shown in Figures B-1 through B-4. Each panel was sectioned through the center of impact with a diamond cutoff wheel, mounted edgewise, and photographed at a magnification of 3.5X.

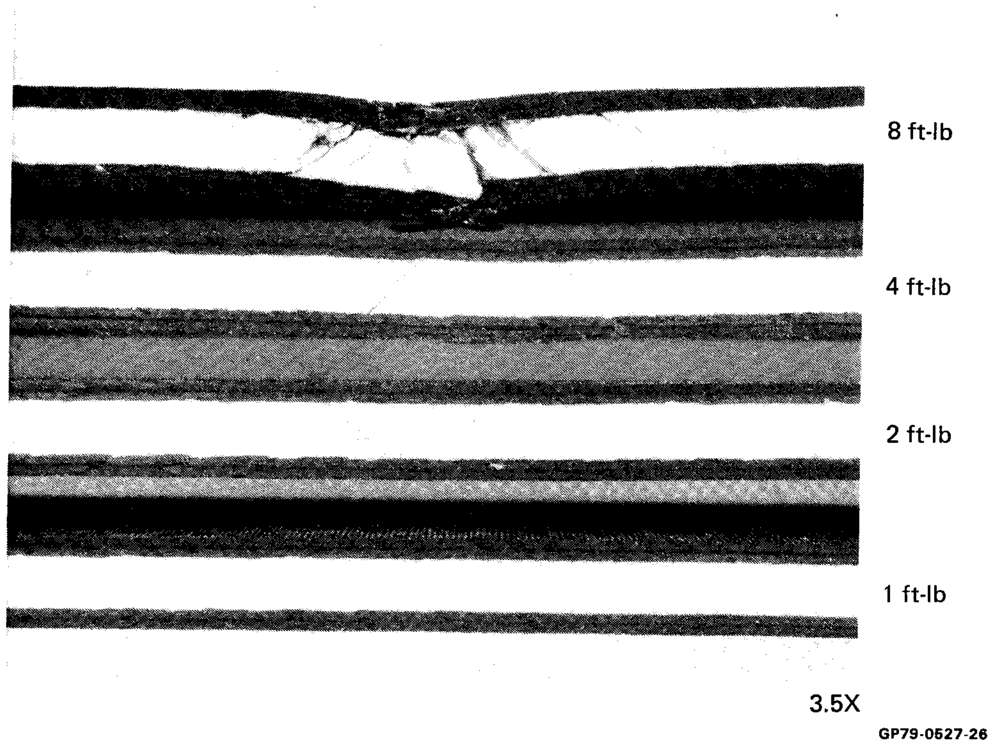

Figure B-1. Cross Sections of Sandwiched HX501/A24X Core After Impact

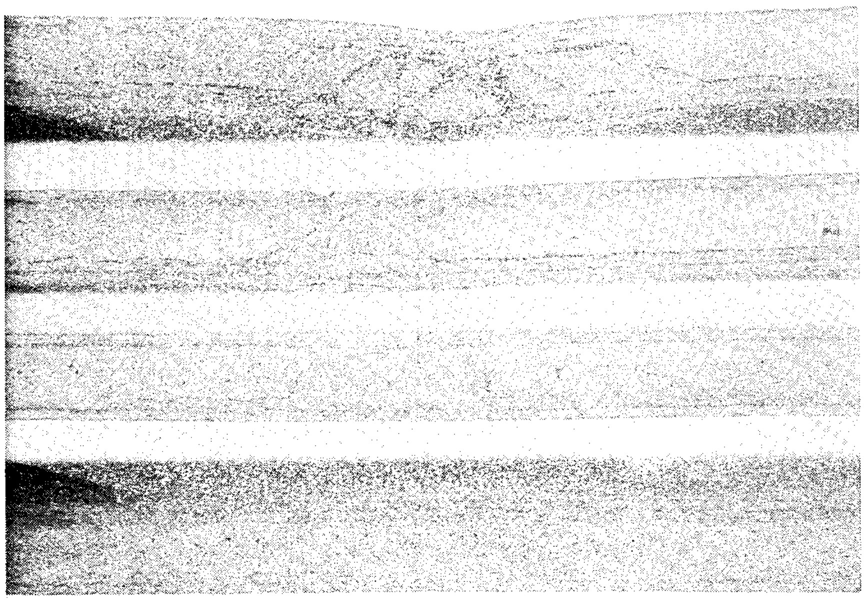

Figure B-2. Cross Sections of Sandwiched HX501/Carbo-Spheres Core After Impact

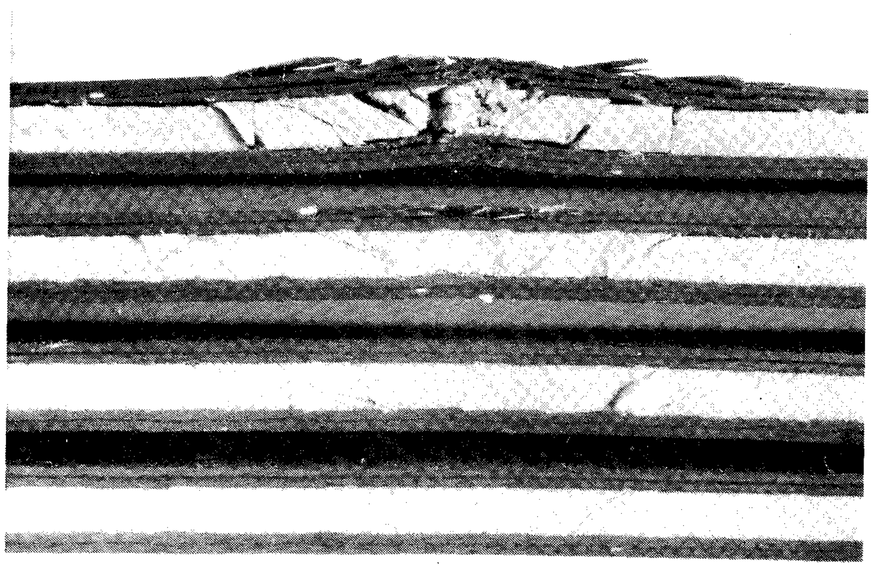

Figure B-3. Cross Sections of Sandwiched HX592/A24X Core After Impact

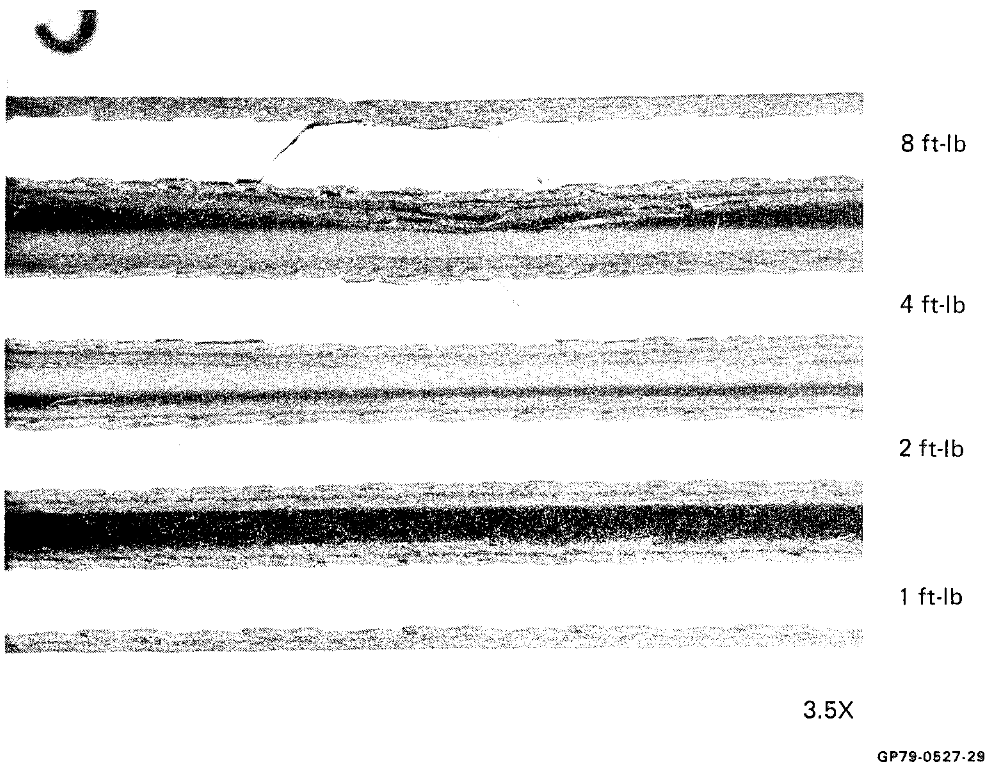

Figure B-4. Cross Sections of Sandwiched Pro-Seal 828 Core After Impact

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